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1 Gradual caldera collapse at Bárðarbunga volcano, Iceland,

2 regulated by lateral magma outflow

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39

40 Abstract

41 Large volcanic eruptions on Earth commonly occur with collapse of the roof of a crustal magma
42 reservoir, forming a caldera. Only a few such collapses occur per century and lack of detailed
43 observations has obscured insight on mechanical interplay between collapse and eruption. We use
44 multi-parameter geophysical and geochemical data to show that the 110 km² and 65 m deep
45 collapse of Bárðarbunga caldera in 2014-15 initiated through withdrawal of magma, and lateral
46 migration through a 47 km long dyke, from a 12 km deep reservoir. Interaction between the
47 pressure exerted by the subsiding reservoir roof and the physical properties of the subsurface flow
48 path explain the gradual, near exponential decline of both collapse rate and the intensity of the 181-
49 day long eruption.

50 _____

51

52 Calderas are 1 - 100 km diameter depressions found in volcanic regions of Earth and other planets.
53 They mainly form by collapse of overburden into a subterranean magma reservoir during large
54 volcanic eruptions, including the largest known super-eruptions (1-8). From 1900 AD to 2014, only
55 six cases have been documented and with varying degrees of detail. The collapses of Katmai in
56 1912 and Pinatubo in 1991 occurred during explosive silicic (andesite-rhyolite) eruptions, the
57 largest of the 20th century. The collapses of Fernandina in 1968, Tolbachik in 1975-76, Miyakejima
58 in 2000 and Piton de la Fournaise in 2007 were associated with mainly effusive mafic (basalt –
59 basaltic andesite) intrusive activity and eruptions (2, 9-12).

60 The consensus from field and modelling studies is that caldera collapse progresses from initial
61 surface downsag to fault-controlled subsidence (1, 8, 13, 14). The limited number of modern
62 examples and the scarcity of geophysical data leaves open the question of whether collapse occurs
63 suddenly or gradually during the course of an eruption. The issue of whether collapse drives magma
64 movement and eruption or eruption drives collapse also remains unresolved. Previous geological,

geophysical, and modeling studies have produced a diverse and inconsistent set of answers to such questions (2, 4, 15, 16). The caldera collapse at Bárðarbunga in central Iceland from August 2014 to February 2015 offers a unique opportunity to address them directly.

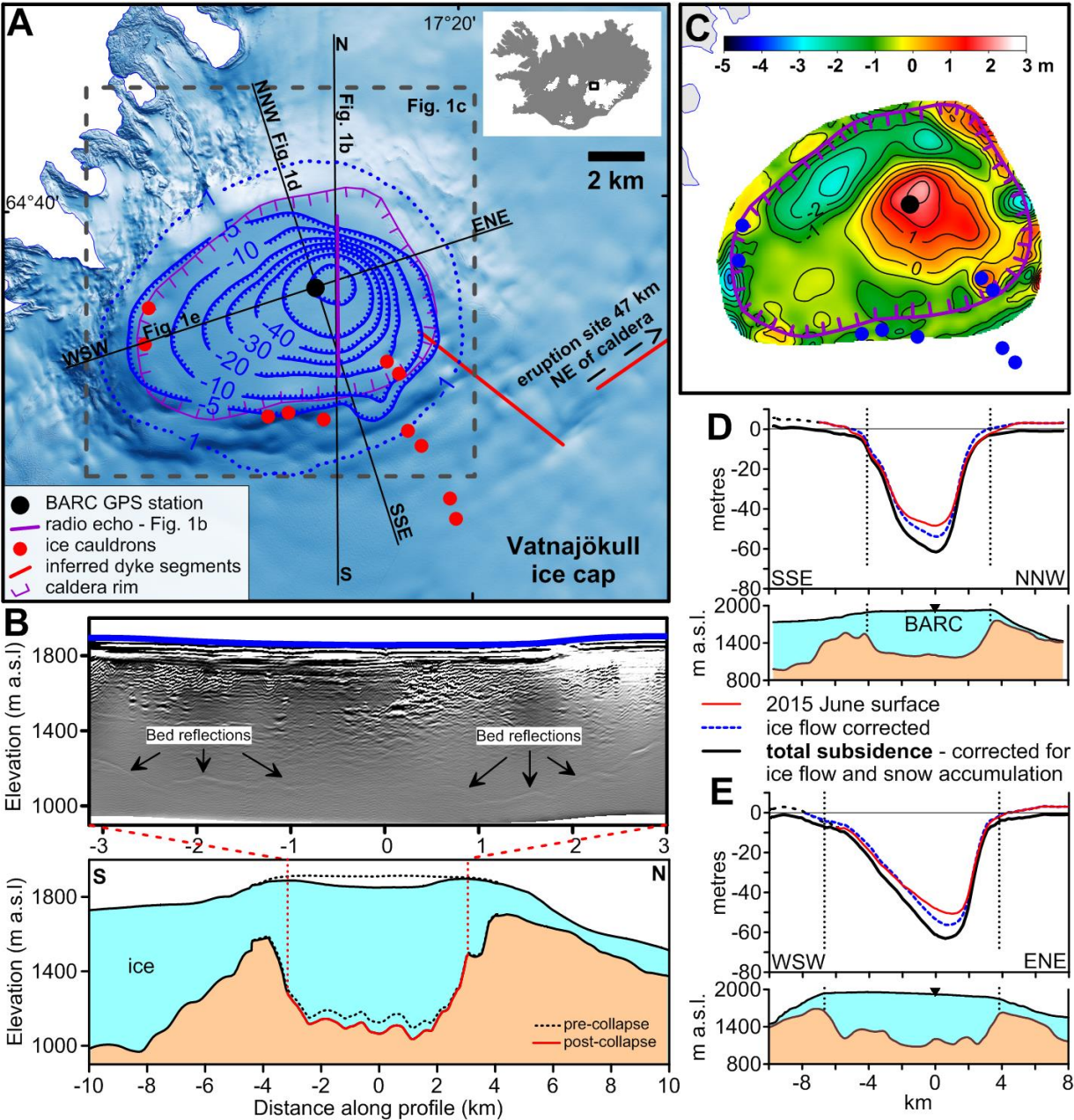


Figure 1. Bárðarbunga and geometry of collapse. A) Map showing the total caldera subsidence (in meters) at the end of collapse in February 2015. B) Minor sustained geothermal activity, monitored from aircraft, increased during the collapse with pre-existing ice cauldrons deepening by up to 50 m and new ones forming at the southern margin and to the southeast of the caldera (24). (B) Radio-echo sounding profile from 3 February, 2015, and a cross-section of the caldera with the collapse.

74 The pre-collapse topography is obtained by subtracting the subsidence observed at the surface. (C)
75 Modelled changes in ice thickness at the end of February 2015 resulting from ice flow in response
76 to caldera collapse (24). D) NNW-SSE and E) WSW-ESE cross-sections as measured in June
77 2015, corrected for winter snow accumulation in 2014-15, measured in June 2015, and modeled
78 vertical ice flow. Subsidence extends 2-3 km beyond the pre-existing caldera rims (dotted lines)
79 where it amounts to 3-11 m.

80 **The Bárdarbunga volcano and the Holuhraun eruption of 2014-15**

81 Bárdarbunga volcano (Fig. 1) and its related fissure swarms form a 150 km long volcanic system on
82 the boundary between the North-American and Eurasian tectonic plates. The volcano resides
83 beneath the Vatnajökull ice cap and has a broadly elliptic 13 by 8 km wide and 500-700 m deep
84 caldera with a long axis trending ENE. About 700-800 m of ice fills the caldera (17, 18). Over 20
85 eruptions have occurred on the fissure swarms outside the caldera in the last 12 centuries, including
86 three that produced 1-4 km³ of magma, but no eruptions are known within the caldera in this period.
87 (19).

88 At 4 UTC on 16 August 2014, the onset of intense seismicity beneath the caldera marked the
89 beginning of a major rifting event (20). The seismic activity was mostly located in the SE-corner of
90 the caldera in the first few hours, but it soon began to propagate out of the caldera towards the SE
91 (Fig. 2). After propagating to about 7 km from the caldera rim, fifteen hours after the onset of
92 seismicity (~19 UTC), the moving earthquake cluster took a 90° turn and started migrating towards
93 the NE. In the two weeks that followed, surface deformation and migration of seismicity indicated
94 that a magmatic dike propagated laterally northeastward for 47 km in the uppermost 6-10 km of the
95 Earth's crust (20, 21). On 31 August, a major effusive eruption began above the far end of the dike;
96 this lasted six months and produced 1.5 ± 0.2 km³ of lava ($\sim 1.4 \pm 0.2$ km³ of bubble-free magma)
97 (22), making it the largest in Iceland (or Europe) since the 1783-84 Laki eruption. Combined with

the $0.5 \pm 0.1 \text{ km}^3$ dyke (20), the total volume of identified intruded and erupted magma was $1.9 \pm 0.3 \text{ km}^3$.

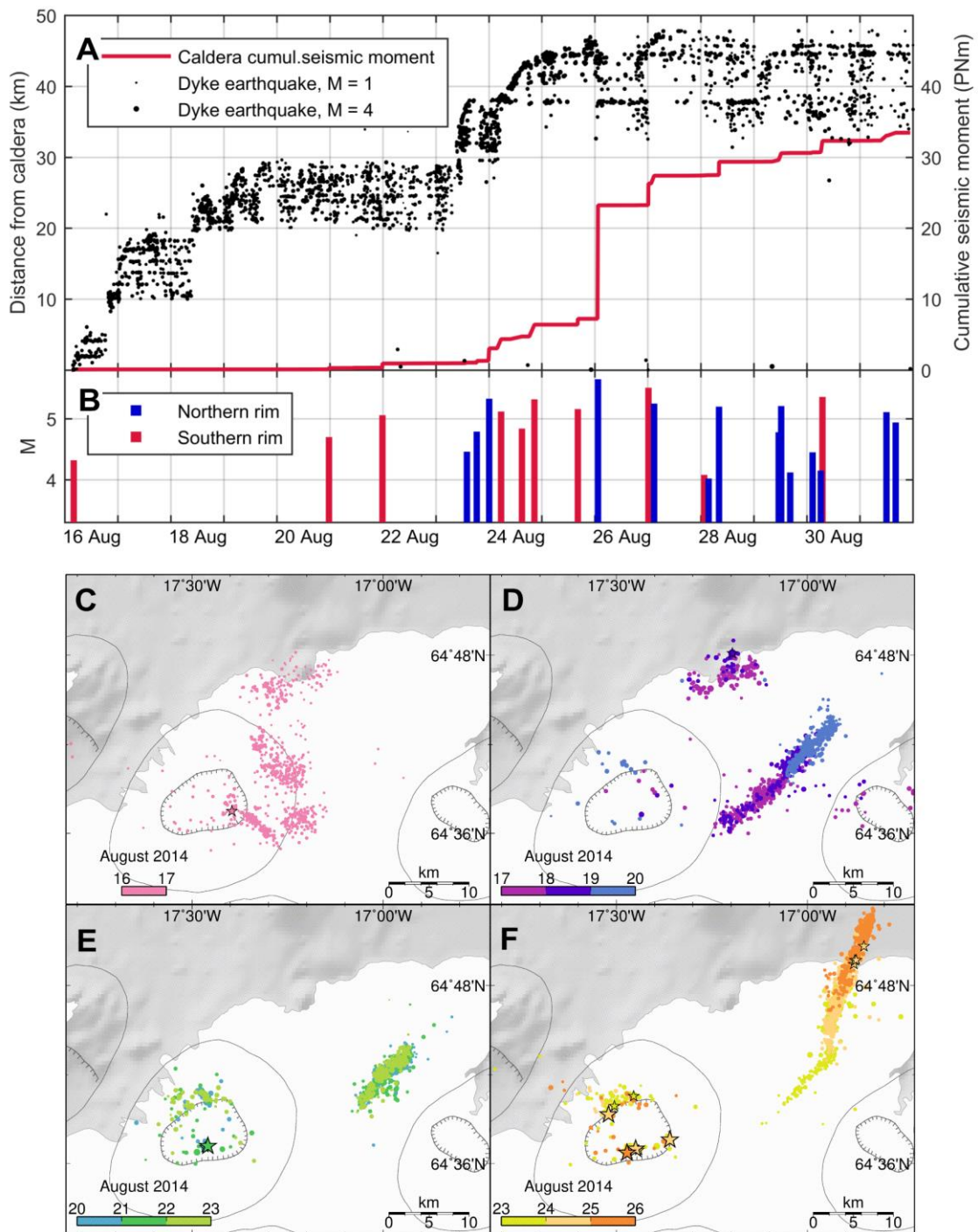
The Onset of Collapse

After the initial seismic activity in the caldera receded late on 16 August, seismicity was relatively minor there until 20 August. At the same time our GPS time-series from stations close to the caldera, suggest that deflation of the magma reservoir started on 16 August (20). On 20 August, caldera seismicity increased progressively with a series of earthquakes of magnitude M4-M5.8 occurring in the following days (Fig. 2). The first two events occurred on the southern caldera rim (M4.7 on 20 August and M5.1 on 21 August). Following these earthquakes, three similar magnitude events occurred on the northern rim on 23 August, followed by four events on the southern rim on 24-25 August. On 26 August activity shifted again to the northern rim with a M5.8 earthquake, the largest in the whole series. These data indicate that significant movement on ring faults started on the south side with the 20-21 August earthquakes, then began on the north side on 23 August, and by 24 August the ring faults on both sides were slipping, a process that did not terminate until at the end of February. Onset of collapse therefore likely occurred on 20 August with the ring fault fully activated on 24 August. If we compare the evolution of the dike together with the seismic moment release of the caldera collapse earthquakes, we can clearly see that the dike migration leads the moment release curve (Fig. 2A). We therefore conclude that onset of collapse resulted from a pressure drop in the reservoir as magma was laterally withdrawn into the propagating dike, with the latter possibly primarily driven by regional tectonic tensional stresses (20).

The volume of the expanding dike on 20 August had reached approximately 0.25 km^3 , increasing to 0.35 km^3 on 24 August (20) with the source of this magma being the reservoir beneath the caldera. The relatively minor caldera seismicity on 17-19 August indicates the material overlying the magma reservoir deformed mostly elastically until it reached a critical failure point of caldera collapse on 20-24 August. If we assume that the entire volume of eruptible magma within the

123 reservoir was $1.9 \pm 0.2 \text{ km}^3$, then the critical volume fraction required to reach the failure point and
 124 trigger the collapse (23) was 0.12-0.21.

125



126

127 **Figure 2. Onset of caldera collapse.** A) Cumulative seismic moment release from caldera

128 earthquakes plotted together with distribution of seismicity along the dike length, using high quality

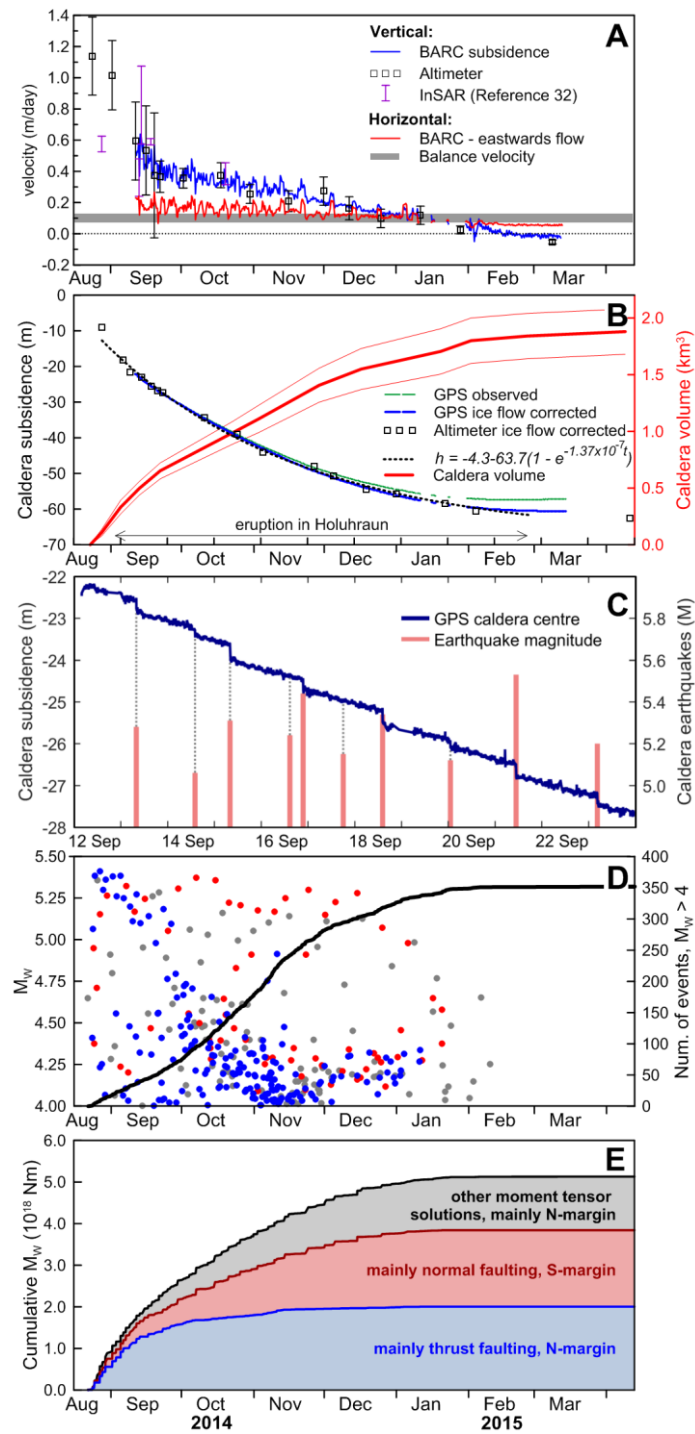
129 relative locations of earthquakes (20), for the time period when the dike progressed away from the
130 caldera. B) Significant caldera earthquakes with magnitudes above M4 plotted as impulses, where
131 the height represents magnitude and color represents location on southern or northern rim. C) Map
132 of NW Vatnajökull showing earthquake epicenters on 16 August, D) 17-19 August, E) 20-22
133 August and F) 23-15 August.

134 **Ice Flow, Subsidence Magnitude and Volume**

135 As we recorded the caldera subsidence mainly on the ice (Fig. 1, Fig. S1), we made corrections and
136 additional measurements to derive the underlying bedrock displacement. Our main data on ice
137 surface changes and ice movements are repeated C-band radar altimeter surveys from aircraft, maps
138 made from optical satellite images and the continuously recording GPS station BARC we set up in
139 the center of the caldera on 13 September. The observed velocities and displacements of the ice
140 surface are displayed on Figs. 3A and 3B. We use these observations to constrain three-
141 dimensional Full-Stokes finite element modelling of ice-flow in response to the collapse (24). The
142 results show concentric flow, towards the point of maximum collapse within the caldera, with
143 maximum ice thickening at the center of ~3 m by February 2015 (Fig. 1C, Fig. S2). The maximum
144 ice surface lowering of 62 ± 2 m, determined by aerial altimeter surveys, gives a maximum bedrock
145 subsidence of 65 ± 3 m. Our data and models show that apart from the concentric flow towards the
146 deepest part of the subsidence (about 1 km east of BARC) horizontal flow was not much affected
147 (Fig. 3A). We therefore conclude that suggestions of a large increase in ice flow out of the caldera
148 during these events (25) cannot be fitted with our data.

149 Bedrock subsidence exceeding 1 m occurred within an area of 110 km^2 that extended beyond the
150 pre-existing caldera (Fig. 1, Fig. S1). After termination of collapse the total subsidence at the pre-
151 existing caldera rims amounted to 3 to 11 meters (Fig. 1D and 1E). Using subglacial radio-echo
152 soundings we observed a down-sagged bedrock surface without any clear signs of fault offset (Fig
153 1B) or indications of water bodies at the ice bedrock interface. The limited resolution resulting

154 from the 600-800 m ice thickness means that we cannot on the basis of the radio-echo results
155 exclude the possibility of steep fault escarpments. However, substantial vertical fault movement at
156 the base of the glacier would result in high strain rates within the basal ice which would instantly
157 fracture the ice fabric and propagate upward. During drainage of subglacial lakes in Iceland, large
158 surface fractures induced by basal motion have been observed repeatedly (26) and can serve here as
159 an analog for the possible surface manifestations of vertical basal motion. The absence of such
160 surface ice fractures at Bárdabunga indicates that no substantial fault escarpment formed at the
161 bottom. The calculated collapse volume is $1.8 \pm 0.2 \text{ km}^3$, not significantly different from the
162 combined volume of erupted and intruded magma (Fig. 3B).



163

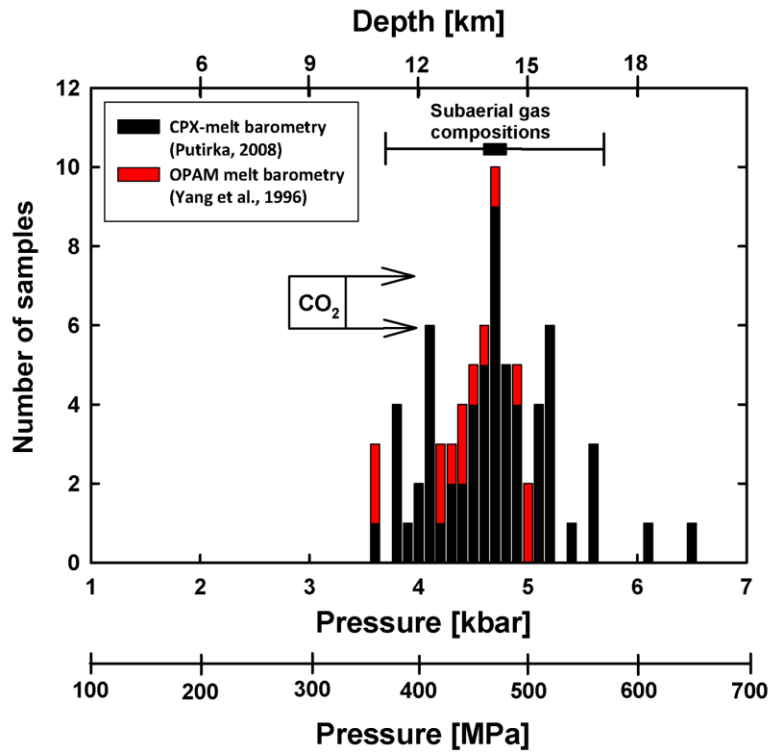
164 **Figure 3. Time series of collapse.** A) Vertical and horizontal velocities measured at the BARC
 165 GPS station in the center of the caldera (Fig. 1A), including the rate of vertical rate of ice surface
 166 subsidence found from altimeter aircraft data and optical satellite photogrammetry. The balance
 167 velocity is obtained by estimating the rate of displacement required to transport the net
 168 accumulation of the area draining ice towards east in the western part of the caldera. InSAR
 169 derived vertical velocities are based on (32). B) Subsidence at the center of the caldera and

170 subsidence volume evolution. The volume of the subsidence is obtained by subtracting the mapped
171 surface from the pre-collapse surface. The caldera subsidence curve is fitted with an equation of the
172 same form as eq. (1). C) High resolution GPS for 12-23 September, showing $M > 5$ earthquakes
173 coinciding with 20-40 cm rapid collapse, superimposed on gradual subsidence. Note that the size of
174 the steps depends on the location of BARC relative to the earthquake centroids, and cannot be used
175 directly to infer the proportion of ring fault slip that ruptured seismically or aseismically. D)
176 Cumulative number of $M > 4$ caldera earthquakes, with magnitude evolution colored in red, blue and
177 grey representing clusters on the southern rim, the northern rim and smaller clusters, respectively
178 (see Fig. S5). E) Cumulative seismic moment for $M > 4$ caldera earthquakes.

179

180 **Magma source depth**

181 Lava chemistry, surface gas composition and geodetic modelling indicate drainage of a magma
182 reservoir at a depth of ~ 12 km. The erupted lava is typical olivine tholeiite with a relatively uniform
183 chemical composition, consistent with efficient homogenization of melts before eruption. Several
184 independent geobarometers (Fig. 4) yield an equilibrium pressure of 350-550 MPa, indicating that
185 melt resided at depths of 11-16 km before the eruption. We obtained a similar result (14 ± 3 km)
186 from analysis of subaerial gas measurements (Fig. 4). This depth concurs with our regional
187 geodetic observations, which are dominated by a deflating source at 8-12 km depth beneath
188 Bárdarbunga, after the cessation of dike-related deformation in mid-September (Figs. S3 and S4).



189

190 **Figure 4. Magma source depth from geobarometric and subaerial gas analysis.** The CO₂-box
 191 indicates the minimum pressure obtained (400 kbar) from density barometry of plagioclase hosted
 192 CO₂-bearing fluid inclusions. The results from the analysis of subaerial gas compositions are based
 193 on FTIR and Multi-GAS measurements (24).

194

195 Seismicity and subsurface structure

196 We used seismic data and Distinct Element Method (DEM) numerical modelling (24), to
 197 characterize the deeper collapse structure as the reactivation of a steeply-inclined ring fault (Fig. 5).
 198 We mostly observed seismicity at depths of 0-9 km beneath the northern and southern caldera rims
 199 (Fig. 5B), with earthquakes being more numerous on the northern rim. This spatial pattern of
 200 seismicity is consistent with fracturing above a deflating magma reservoir that was elliptical in
 201 plan-view (27). In cross-section, the hypocenters indicate a steeply (~80°) outwards-dipping fault in
 202 the northern cluster, while the southern cluster they indicate a vertical or near-vertical fault dip. A
 203 series of DEM forward simulations of a magma chamber and ring fault system, as constrained by

the hypocenter distribution and by the geobarometry data, tested the above structural interpretation against the observed NNW-SSE subsidence profile. The models indicate that a pre-existing and relatively low friction (coefficient of 0.1-0.2) ring-fault system controlled the subsidence at depth (Fig. 5C, D). Our best fitting models had preexisting faults dipping out at 80-85° from the caldera center on the north side and at 85-90° toward the caldera center on the south side. The modeled pre-existing faults lay at 1-2 km below the surface on the north side and 3-4 km on the south side. Modeling of a more complex fault geometry or the inclusion of greater material heterogeneity may further improve the data fit, but presently lacks robust geophysical constraints. The arrangement of an outward dipping fault on one side of a caldera and an inward-dipping fault on the other is typical of ‘asymmetric’ or ‘trapdoor-like’ collapses produced in past analog and numerical modeling studies (8, 28, 29). It also occurs at Glencoe (29) and Tendurek (30) volcanoes. Finally, our finding is consistent with past seismological results that defined a very similar ring-fault geometry during the last period of activity at Bardarbunga in 1996 (31).

Through regional moment tensor (MT) inversion, we infer that the source mechanisms of 77 $M > 5$ events (Fig. S5) confined to two clusters beneath the northern and southern rim regions show contributions of both shear and non-shear components. The shear components indicate possible ruptures of segments on the ring fault. Shear failure on inward dipping ring faults, or the sudden injection of magma in horizontal fissures forming sills have been proposed (32) to explain the shear components of the observed earthquakes at Bárðarbunga. We, however, narrowed down on plausible solutions by using the micro-earthquakes (Fig. 5A). The moment tensor solutions are well constrained, but the inferred dip of the shear plane we obtain is uncertain since the non-shear component, in this case a negative, sub-vertical compensated linear vector dipole (vCLVD), is dominant. As a result, the shear orientation obtained depends very much on the decomposition approach.

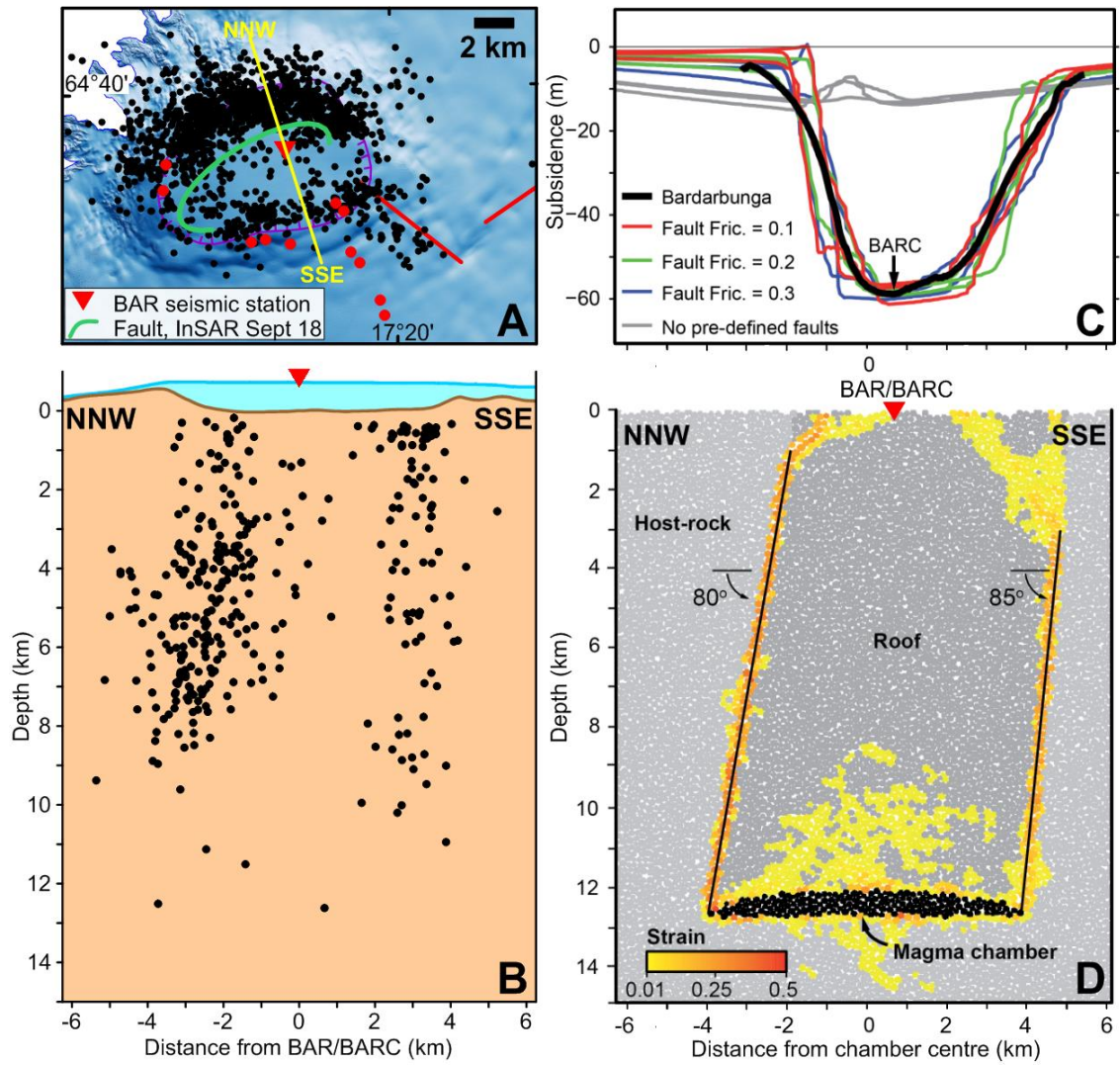
By using the constraint of the steeply outward dipping ring fault on the northern cluster we derive a MT solution that is a combination of a negative vCLVD and steep E-W striking reverse faulting

230 (Fig. 3D, 3E and Fig. S5). In contrast, standard decomposition of the northern cluster MTs provides
231 normal faulting along steep N-S striking planes, a result that is inconsistent with the observed main
232 fault orientation. The southern cluster MTs are consistent with being composed of families (33) of
233 steep normal faulting earthquakes.

234 The large, negative $v\text{CLVD}$ indicates a combination of downward contraction and horizontal
235 expansion, as has been observed in mines as well as in volcanic calderas during collapses (e.g. 31,
236 34). This could imply failure of support structures directly above or even within the magmatic
237 reservoir, or the sudden response of the reservoir fluid to vertical compression.

238 **Temporal development of subsidence and related seismicity**

239 Subsidence occurred gradually during the eruption (Fig. 3B). From an initial rate in the caldera
240 center of ~ 1 m/day during the first 20 days (Fig. 3B), subsidence declined in a near exponential
241 manner with time (24). Subsidence terminated when the eruption ended in February 2015. We can
242 associate some of the $M > 5$ caldera earthquakes, during the first couple of months of activity, with
243 drops of 10-40 cm, but subsidence was otherwise continuous (Fig. 3C). The gradual decline in the
244 rates of subsidence and caldera volume growth is mirrored by a decline in the cumulative seismic
245 moment, the latter reflecting a decrease in the number of larger earthquakes with time (Fig. 3D, 3E).
246 Nonetheless, in terms of the cumulative seismic moment of 5.07×10^{18} Nm for the $M > 4.0$ events,
247 this collapse is the second largest recorded, after that of Katmai (1912) (35). The geodetic moment
248 depends on the shear modulus, the fault area and the amount of slip assumed. The shear modulus
249 could be very low in regions of intense faulting such as on a caldera ring fault. The possible range
250 of the geodetic moment is found by considering a ring fault reaching from the surface to 12 km
251 depth, 60 m of slip and a shear modulus over a wide range, 2-20 GPa. This results in a moment of
252 4×10^{19} - 4×10^{20} Nm, or 10-100 times the cumulative seismic moment of the earthquakes. This
253 difference is consistent with the modeling of surface deformation observed during one of the events
254 (Fig S7).



255

256 **Figure 5: Fault geometry and collapse modelling:** A) Earthquakes 1 August – 17 October 2014,
 257 B) seismicity along a 2-4 km wide strip on the NNW-SSE cross section, depth relative to bedrock
 258 caldera floor. C-D) Two-dimensional DEM modeling of the collapse, constrained by subsidence
 259 geometry, earthquake locations in (B), and the geobarometry (Fig. 4). The geometry illustrated in
 260 (D) obtained the best agreement with the observations. The color scale shows the maximum finite
 261 shear strain. Surface displacement profiles for different pre-existing fault frictions are provided in
 262 (C). Three model realizations are shown for each friction value.

263 **Caldera-flowpath interaction and piston collapse modeling**

264 We see a short-term (multi-hourly) mechanical coupling of the collapsing caldera and the distal dike
265 (south of eruption site) in the timing of earthquakes in the dike and at the caldera (Fig. 6A). Within
266 a six-hour window before and after large caldera earthquakes the frequency of dike earthquakes was
267 increased relative to background rate (24). We observed this pattern in the data after the beginning
268 of October 2014, when the dyke had stopped propagating and a quasi-steady magma flow path had
269 developed, until February 2015 when seismic activity stopped. For the three hours after caldera
270 earthquakes with magnitude $M > 4.6$, as well as for the three hours before caldera earthquakes with
271 $M > 4.0$, the increase in seismicity was significant (24) ($p = 0.05$; Fig. 6, Fig. S8).

272 At Bárðarbunga communication therefore existed between caldera subsidence events and pressure
273 changes in a conduit up to 47 km away. Spatiotemporal patterns of tilt at Kilauea Volcano, Hawaii,
274 show a similar phenomenon that can be explained by the propagation of pressure transients within
275 an elastically deformable dyke (36). By analogy, we can make the interpretation that caldera
276 earthquakes may generate a pressure pulse that leads to increased seismicity at the end of the dike.
277 The communication could be two-way, although it is difficult to explain a pressure pulse from the
278 dike towards the caldera. One possibility is that readjustment of the dike (e.g. sudden unblocking)
279 can increase the dike volume slightly and subsequently lower the magma pressure which then
280 translates back to the caldera. The communication may also be entirely one-way, from the caldera
281 to the dike: smaller caldera earthquakes, and/or aseismic deformation at depth just above the
282 magma chamber may precede a large caldera earthquake, increasing dike pressure and dike
283 seismicity.

284 We explain the longer term (weeks to months scale) coupling in the form of the gradually declining
285 rates of caldera subsidence, caldera volume change and lava eruption (Figs. 3B, 6B) with a model
286 of a collapsing piston overlying a pressurized magma chamber. We assume that the chamber
287 pressure and fault friction each partially support the piston weight (24). Drainage of magma reduces

the chamber pressure and causes piston subsidence (Fig. S6). This in turn raises the chamber pressure, leading to a feedback loop that maintains quasi-constant pressure at the magma chamber top, and drives further magma drainage. The pressure feeding the eruption drops, however, due to the reduction in hydraulic head of magma over time. Kumagai et al. (37) also used a piston model to explain caldera collapse at Miyakejima in 2000, but in their model no change in hydraulic head was assumed and outflow rate was held constant.

Assuming that the time-averaged resistive force due to friction on the ring faults remains constant, and that magma flow is laminar through a cylindrical pipe with radius r , and conduit length L , with $L \gg r$, then

$$\Delta P \approx \Delta P_0 e^{-\frac{\pi \rho g r^4}{8 A \eta L} t} \quad (1)$$

Where ΔP is the driving overpressure, ΔP_0 is the initial driving overpressure, ρ is the density of the magma, g is gravitational acceleration, A is the cross-sectional area of the magma chamber, η is the dynamic viscosity of the magma and t is time (24). We estimated ΔP_0 and the constant in the exponent, assuming that the measured subsidence within the caldera represents the decrease in magma chamber height with time (Fig 3B). Note, this represents a minimum estimate for ΔP_0 , as there may also have been dilation at depth. The model also fits the measured caldera volume change (Fig. 3B) and eruption rate (Fig. 6B). This model predicts the same form of decay in flow rate (exponential) as the standard ‘Wedge’ model of depressurisation of an overpressured magma body (38), but by a different mechanism. The feedback mechanism of re-pressurisation from the ongoing piston collapse enhanced the length and speed of dike propagation, and the duration of the eruption. In this model, therefore, both the eruption drives the collapse and collapse drives the eruption.

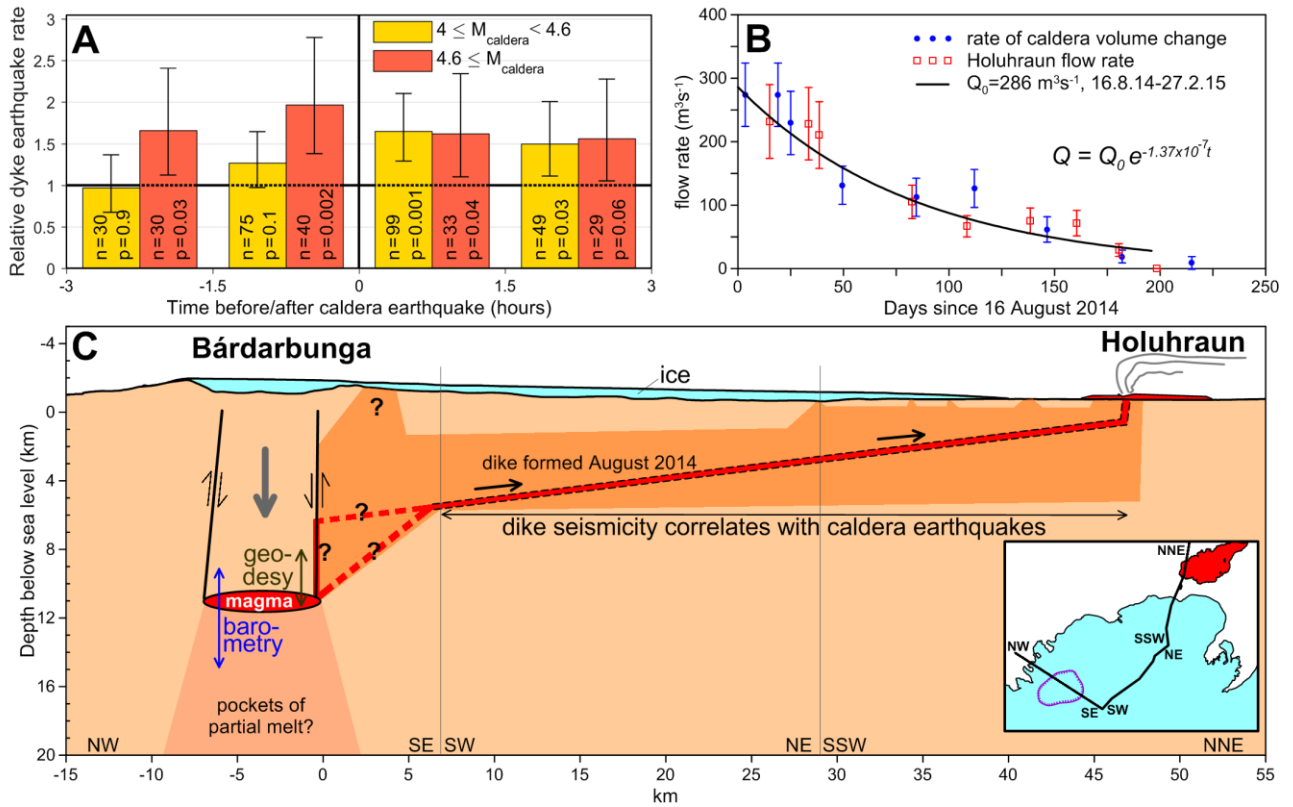


Figure 6. Caldera - magma flowpath interaction. A) Rate of dike earthquakes relative to background levels before and after significant caldera earthquakes of magnitude $>M4$. The p-values indicate the two sided significance and n is the number of earthquakes used. Error bars indicate 90% confidence intervals (24). B) Exponential model of magma flow rate constrained by caldera GPS subsidence (24) compared with rate of volume change in caldera and eruption rate in Holuhraun. The eruption stopped on Day 194 (27 February, 2015) before the driving pressure reaches zero, as expected if the conduit becomes clogged by solidifying magma as the flow rate drops. C) Schematic cross-section of caldera - magma chamber - pipe-like magma flow path and eruption site after dike formation (20, 21). The inferred magma chamber is set at 12 km below bedrock caldera floor. It is possible that magma ascended first along the ring fault before forming the dyke above 6-10 km depth. We indicate the constraints on depth to magma chamber from geobarometry with a blue arrow and from geodesy with a green arrow.

324 Overview and implications

325 Table 1 contextualizes the key features of the 2014-15 Bardarbunga collapse with respect to those
 326 of the seven collapses instrumentally monitored to date. The areal extent of the Bardarbunga
 327 collapse (110 km²) is the largest yet observed historically and is comparable to that associated with
 328 major silicic eruptions in the geological record (6). The total subsidence (65 m) is one to two orders
 329 of magnitude smaller than all past collapses listed here, but the large area means that it has the
 330 fourth largest collapse volume (1.8 km³) overall. The erupted volume (1.4 km³) is the largest of the
 331 observed mafic collapses so far, although considerable uncertainty surrounds the volumes
 332 associated with the collapse of Fernandina. In volume terms, both the silicic eruptions and collapses
 333 of Katmai and Pinatubo were twice to six times larger. The cumulative seismic energy release at
 334 Bardarbunga (25 x 10¹³ J, see Table 1) is dwarfed by that of Katmai (1600 x 10¹³ J) and similar to
 335 Miyakejima (22 x 10¹³ J), despite the much smaller area of the latter (1.9 km²). This is explained by
 336 the much greater subsidence at Miyakejima (>1600 m). The gradual collapse of Bardarbunga had
 337 the second longest duration (190 days) yet recorded. Only the duration of collapse at Tolbachik
 338 (515 days) exceeds it. Finally, Bardarbunga has the longest confirmed length of an associated lateral
 339 intrusion (48 km) and the longest distance to the main vent (40 km).

Volcano	Year	Magma	Maximum subsidence (m)	Collapse Duration (days)	Collapse Area (km ²)	Collapse Volume (km ³)	Reservoir Depth (km)	Intrusion Volume (km ³) ^(a)	Erupted Volume (km ³) ^(b)	Total Magma Volume (km ³)	Distance to Vent ^(c) (km)	Intrusion Length ^(d) (km)	Seismic Energy (x 10 ¹³ J) ^(e)	Max. EQ ^(f)
Bardarbunga	2015	Basalt	~ 61	150	110	1.8	11-16	0.5	1.5	2	46	48	25	5.4
La Reunion	2007	Basalt	~ 450	2	0.82	0.1	2-3	0.02	0.14	0.16	7	7	?	3.2
Miyakejima	2000	Basalt	~ 1600	40	1.9	0.6	4-7	1.2	0.01	1.21	5.6	35	22	5.6
Tolbachik	1976	Basalt	> 500	515	2.5	0.35	4-6?	?	1.2	> 1.2	28	~ 45	?	2.9
Fernandina	1969	Basalt	~ 350	12	7	2	?	?	0.2	> 0.2	10.5?	10.5?	2	5.2
Katmai	1912	Rhyolite	> 1300	3	8.8	5.5	2-5	?	13.5	> 13.5	10	10	1600	7
<i>Pinatubo*</i>	1991	<i>Dacite</i>	~ 900	2	4	2	7-11	?	4.5	4.5	1	4	2	5.7

340

341 **Table 1: Instrumentally-monitored caldera collapses since 1900 AD.**

342 * Note that all caldera collapses except Pinatubo formed in association with lateral withdrawal and intrusion of
 343 magma.

344 **References for data:** *Bardarbunga*: (20); this study; *La Reunion*: (12,16,44-46); *Miyakejima*: (2, 11, 34, 47-
345 49); *Tolbachik*: (50-53); *Fernandina*: (2, 9, 54); *Katmai*: (35, 41, 55); *Pinatubo*: (2, 15, 42, 43, 56)

346 ^(a) Intrusion volume values are typically constrained by inversions of data from geodetic networks, and so are available
347 only for the most recent events.

348 ^(b) Erupted volumes are given as Dense Rock Equivalent (DRE) – i.e. with porosity removed.

349 ^(c) Distance measured from center of caldera to most distant known vent active during collapse.

350 ^(d) Estimated horizontal length of the intrusion, from locations of seismicity and/or inversions of geodetic data in all
351 cases except Katmai. For Katmai and Fernandina, intrusion length is estimated as the distance from caldera to vent
352 and is hence a minimum value.

353 ^(e) Cumulative seismic energy release calculated by converting the cumulative scalar moments (M_0) by using a factor of
354 5×10^{-5} (from energy-moment relationship determined by Kanamori et al. (57))

355 ^(f) Maximum earthquake magnitude associated with caldera formation. Magnitude determined from surface waves,
356 M_s , is given for Tolbachik (53), Katmai (35) and Fernandina (54). For La Reunion, M_d is used (12, 44). For Miyakejima
357 and Bardarbunga, the maximum moment magnitude (M_w) for collapse-related VLP events is given (34, 58, this study).

358

359 Our data and modelling show that withdrawal and eruption of magma triggered the collapse at
360 Bardarbunga. For the likely depth to diameter ratio of the magma reservoir, the critical volume
361 fraction required to trigger the onset of collapse (0.12-0.21) was much lower than that predicted by
362 past analytical and analogue modelling (23, 39). A similar inference of low critical volume fractions
363 at La Reunion and Miyakejima (16) was explained as a consequence of the reactivation of pre-
364 existing ring faults, a proposition in line with our observations and analysis of the Bardarbunga
365 collapse.

366 Nonetheless, we also show that there is a tight mechanical interplay between collapse and eruption
367 throughout the process once collapse has started, with eruption driving collapse and vice versa on
368 both hourly and eruption-long time scales. For the longer time-scale coupling, the results also show
369 that the physical properties of both the magma chamber roof and the magma pathway regulate
370 caldera collapse and magma outflow rate. Consequently, collapse at Bárðarbunga occurred
371 gradually and at a steadily (exponentially) declining rate. This is a very similar pattern to that
372 inferred for the 1968 Fernandina collapse (2, 16). In contrast to some model predictions (40) and to

373 the 2007 collapse of Piton de la Fournaise (*16*), we found no evidence for rapid and sustained
374 pressure increase in the magma chamber as a result of collapse, possibly due to substantial ductile
375 behavior of the roof of the larger and deeper Bardarbunga magma chamber (*13, 16*).

376 The question of whether or to what extent our understanding of caldera collapse at mafic volcanoes
377 such as Bardarbunga is transferrable to large silicic systems remains an open one. On the one hand
378 the gradual nature of collapse at Bardarbunga and Fernandina contrasts with the highly punctuated
379 collapse style inferred during explosive silicic eruptions like Katmai and Pinatubo (*2, 41*). In
380 addition, collapse at silicic volcanoes is generally considered to be triggered by eruption through a
381 central vent rather than through the lateral withdrawal mechanism seen at Bardarbunga. On the
382 other hand, of the two instrumentally monitored silicic collapses, the most silicic, Katmai was also
383 clearly associated with a lateral withdrawal. This mechanism could therefore be more widespread at
384 silicic calderas than commonly considered. In addition, the locations and mechanisms of the large,
385 apparently collapse-related earthquakes interpreted to denote punctuated collapses of Katmai and
386 Pinatubo are poorly constrained, such that a regional tectonic origin for them cannot be precluded
387 (*15, 35, 42, 43*). Consequently, Bardarbunga 2014-15 provides our clearest picture yet of how
388 caldera collapse can be triggered during large eruptions, and how the dynamics of the subterranean
389 magma flow path and the interaction with magma reservoir pressure regulates eruption rates and the
390 rate of collapse.

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413 References

- 414 1. M. Branney, V. Acocella, "Calderas" in *The Encyclopedia of Volcanoes*, H. Sigurdsson, B. Houghton, H.
415 Rymer, Eds. (Academic Press, Academic Press, Heidelberg, Amsterdam, Boston, ed. 2, 2015), pp. 229-315.
- 416 2. J. Stix, T. Kobayashi, Magma dynamics and collapse mechanisms during four historic caldera-forming
417 events. *J. Geophys. Res.* **113**, JB005073 (2008).
- 418 3. A. R. McBirney, A historical note on the origin of calderas. *J. Volcanol. Geotherm. Res.* **42**, 303-306
419 (1990).
- 420 4. R. S. J. Sparks, P.W. Francis, R. D. Hamer, R. J. Pankhurst, L. O. O'callaghan, R. S. Thorpe, R. Page,
421 Ignimbrites of the Cerro Galán caldera, NW Argentina. *J. Volcanol. Geotherm. Res.* **24**, 205-248 (1985).
- 422 5. T. H. Druitt, R. S. J. Sparks, On the formation of calderas during ignimbrite eruptions. *Nature* **310**, 679-
423 681 (1984).
- 424 6. P. W. Lipman, Subsidence of ash-flow calderas: relation to caldera size and magma-chamber geometry.
425 *Bull. Volc.*, **59**, 198-218 (1997).
- 426 7. V. Acocella, Understanding caldera structure and development: an overview of analogue models
427 compared to natural calderas. *Earth Sci. Rev.*, **125**, 125-160 (2007).
- 428 8. O. Roche, T. H. Druitt, O. Merle, Experimental study of caldera formation. *J. Geophys. Res.* **105**, 395-416
429 (2001).

9. T. Simkin, K. A. Howard, Caldera collapse in the Galapagos Islands, 1968: The largest known collapse since 1912 followed a flank eruption and explosive volcanism within the caldera. *Science* **169**, 429–437 (1970).
10. S. A. Fedotov, Y. K. Markhinin, *The Great Tolbachik Fissure Eruption. Geological and Geophysical Data 1975-1976*. (Cambridge University Press, Cambridge, 2011).
11. N. Geshi, T. Shimano, S. Chiba, Caldera collapse during the 2000 eruption of Miyakejima Volcano, Japan. *Bull. Volcanol.* **64**, 55-68 (2002).
12. T. Staudacher, V. Ferrazzini, A. Peltier, P. Kowalski, P. Boissier, P. Catherine, F. Lauret, F. Massin, The April 2007 eruption and the Dolomieu crater collapse, two major events at Piton de la Fournaise (La Réunion Island, Indian Ocean). *J. Volcanol. Geotherm. Res.* **184**, 126-137 (2009).
13. E. P. Holohan, M. P. J. Schöpfer, J. J. Walsh, J. J. Stress evolution during caldera collapse. *Earth Planet. Sc. Lett.* **421**, 139-151 (2015).
14. K. V. Cashman, G. Giordano, Calderas and magma reservoirs. *J. Volcanol. Geotherm. Res.* **288**, 28-45 (2014).
15. J. Battaglia, C. H. Thurber, J.-L. Got, C. A. Rowe, R. A. White, Precise relocation of earthquakes following the 15 June 1991 eruption of Mount Pinatubo (Philippines). *J. Geophys. Res.* **109**, B7 (2004).
16. L. Michon, F. Massin, V. Famin, V. Ferrazzini, G. Roult, Basaltic calderas: Collapse dynamics, edifice deformation, and variations of magma withdrawal. *J. Geophys. Res.* **116**, B3 (2011).
17. H. Björnsson, P. Einarsson, Volcanoes beneath Vatnajökull, Iceland: evidence from radio-echo sounding, earthquakes and jökulhlaups. *Jökull* **40**, 147-148 (1990).
18. M. T. Gudmundsson, T. Högnadóttir, Volcanic systems and calderas in the Vatnajökull region, central Iceland, constraints on crustal structure from gravity data. *Journal of Geodynamics*, **43**, 153-169 (2007).
19. T. Thordarson, G. Larsen, Volcanism in Iceland in historical time: Volcano types, eruption styles and eruption history. *J. Geodyn.* **43**, 118-152 (2007).
20. F. Sigmundsson, A. Hooper, S. Hreinsdóttir, K. S. Vogfjörð, B. G. Ófeigsson, E. R. Heimisson, S. Dumont, M. Parks, K. Spaans, G. B. Gudmundsson, V. Drouin, T. Árnadóttir, K. Jónsdóttir, M. T. Gudmundsson, T. Högnadóttir, H. M. Fridriksdóttir, M. Hensch, P. Einarsson, E. Magnússon, S. Samsonov, B. Brandsdóttir, R. S. White, T. Ágústssdóttir, T. Greenfield, R. G. Green, A. R. Hjartardóttir, R. Pedersen, R. A. Bennett, H. Geirsson, P. C. La Femina, H. Björnsson, F. Pálsson, E. Sturkell, C. J. Bean, M. Möllhoff, A. K. Braiden, E. P. S. Eibl, Segmented lateral dyke growth in a rifting event at Bárðarbunga volcanic system. *Nature* **517**, 191-195 (2015).
21. T. Ágústssdóttir, J. Woods, T. Greenfield, R. G. Green, R. S. White, T. Winder, B. Brandsdóttir, S. Steinthórsson, H. Soosalu, Strike-slip faulting during the 2014 Bárðarbunga-Holuhraun dike intrusion, central Iceland. *Geophys. Res. Lett.* (accepted). DOI: 10.1002/2015GL067423
22. S. R. Gíslason, G. Stefánsdóttir, M. A. Pfeffer, S. Barsotti, Th. Jóhannsson, I. Goleczka, E. Bali, O. Sigmarsson, A. Stefánsson, N. S. Keller, A. Sigurdsson, B. Bergsson, B. Galle, V. C. Jacobo, S. Arellano, A. Aiuppa, E. S. Eiríksdóttir, S. Jakobsson, G. H. Gudfinnsson, S. A. Halldórsson, H. Gunnarsson, B. Haddadi, I. Jónsdóttir, Th. Thordarson, M. Riishuus, Th. Högnadóttir, T. Dürig, G. B. M. Pedersen, A. Höskuldsson, M. T.

467 Gudmundsson, Environmental pressure from the 2014–15 eruption of Bárðarbunga volcano, Iceland.
 468 *Geochem. Perspect. Lett.*, **1**, 84-93 (2015).

469 23. O. Roche, O., T. H. Druitt, Onset of caldera collapse during ignimbrite eruptions. *Earth Planet. Sci. Lett.*,
 470 **191**(3), 191-202 (2001).

471 24. Materials and methods are available as supplementary materials on Science Online.

472 25. J. Browning, A. Gudmundsson, Surface displacements resulting from magma-chamber roof subsidence,
 473 with application to the 2014-2015 Bardarbunga-Holuhraun volcanotectonic episode in Iceland. *J. Volcanol.*
 474 *Geotherm. Res.* **308**, 82-98 (2015).

475 26. H. Björnsson, Hydrology of ice caps in volcanic regions. *Soc. Sci. Isl.* 45, 139pp (1988).

476 27. E. P. Holohan, V. R. Troll, B. Van Wyk de Vries, J. J. Walsh, T. R. Walter, Unzipping Long Valley: an
 477 explanation for vent migration during an elliptical ring fracture eruption. *Geology* **36**, 323-326 (2008).

478 28. E. P. Holohan, T. R. Walter, M.P. Schöpfer, J. J. Walsh, B. Wyk de Vries, V. R. Troll, Origins of oblique-slip
 479 faulting during caldera subsidence. *J. Geophys. Res.* **118**(4), 1778-1794 (2013).

480 29. C. Clough, H. Maufe, E. Baley, The cauldron subsidence of Glen-Coe, and the associated igneous
 481 phenomena. *Q.J.Soc. Lond.* **65**, 611–678 (1909).

482 30. H. Bathke, M. Nikhoo, E.P. Holohan, T.R. Walter, Insights into the 3D architecture of an active caldera
 483 ring-fault at Tendürek volcano through modeling of geodetic data. *Earth. Planet. Sci. Lett.* **422**:157-168
 484 (2015).

485 31. A. Fichtner, H. Tkalcic, Insights into the kinematics of a volcanic caldera drop: Probabilistic finite-source
 486 inversion of the 1996 Bardarbunga, Iceland, earthquake. *Earth Planet. Sc. Lett.* **297**, 607-615 (2010).

487 32. B. Riel, P. Milillo, M. Simons, P. Lundgren, H. Kanamori, H., S. Samsonov, The collapse of Bárðarbunga
 488 Caldera, Iceland. *Geophys. J. Int.* **202**, 446-453 (2015).

489 33. S. Cesca, A. T. Sen, T. Dahm, Seismicity monitoring by cluster analysis of moment tensors. *Geophys. J.*
 490 *Int.* **196**, 1813-1826 (2013).

491 34. A. Shuler, G. Ekström, M. Nettles, Physical mechanisms for vertical-CLVD earthquakes at active
 492 volcanoes. *J. Geophys. Res.* **118**(4), 1569-1586 (2013).

493 35. K. Abe, Seismicity of the caldera-making eruption of Mount Katmai, Alaska in 1912. *B. Seismol. Soc. Am.*
 494 **82**, 175-191 (1992).

495 36. C. P. Montagna, H. M. Gonnermann, Magma flow between summit and Pu`u `O`o at Kilauea Volcano,
 496 Hawaii. *Geochem. Geophys. Geosy.* **14**, 2232–2246 (2013).

497 37. H. Kumagai, T. Ohminato, M. Nakano, M. Ooi, A. Kubo, H. Inoue, J. Oikawa, Very-long-period seismic
 498 signals and caldera formation at Miyake Island, Japan. *Sci.* **293**, 687-690 (2001).

499 38. G. Wadge, Steady state volcanism: evidence from eruption histories of polygenetic volcanoes.
 500 *J. Geophys. Res.* **87**, B5: 4035-4049 (1982).

501 39. A. Geyer, A. Folch, J. Martí, Relationship between caldera collapse and magma chamber withdrawal: an
 502 experimental approach. *J. Volcanol. Geotherm. Res.* **157**, 375-386 (2006).

503 40. A. Folch, J. Marti, Time-dependent chamber and vent conditions during explosive caldera-forming
504 eruptions. *Earth Planet. Sc. Lett.* **280**, 246-253 (2009).

505 41. W. Hildreth, J. Fierstein, Katmai volcanic cluster and the great eruption of 1912. *Geophys. J. Int.* **112**,
506 446-453 (2000).

507 42. B. C. Bautista, M. L. P. Bautista, R. S. Stein, E. S. Barcelona, R. S. Punongbayan, E. P. Laguerta, A. R.
508 Rasdas, G. Ambubuyog, E. Q. Amin, "Relationship of regional and local structures to Mount Pinatubo
509 activity" in *Fire and Mud: Eruptions and Lahars of Mount Pinatubo, Philippines. PHIVOLCS*, C. G. Newhall, R.
510 S. Punongbayan, Eds. (University of Washington Press, Quezon City, 1996), pp. 351-370.

511 43. J. Mori, R. A. White, D. H. Harlow, P. Okubo, J. A. Power, R. P. Hoblitt, E. P. Laguerta, A. Lanuza, B. C.
512 Bautista, "Volcanic earth quakes following the 1991 climactic eruption of Mount Pinatubo: strong seismicity
513 during a waning eruption" in *Fire and Mud: Eruptions and Lahars of Mount Pinatubo, Philippines. PHIVOLCS*.
514 C. G. Newhall, R. S. Punongbayan, Eds. (University of Washington Press, Quezon City, 1996), pp. 339-350.

515 44. L. Michon, T. Staudacher, V. Ferrazzini, P. Bachèlery, J. Marti, April 2007 collapse of Piton de la
516 Fournaise: a new example of caldera formation. *Geophys. Res. Lett.*, **34**(21) (2007).

517 45. F. R. Fontaine, G. Roult, L. Michon, G. Barruol, A. Di Muro, The 2007 eruptions and caldera collapse of
518 the Piton de la Fournaise volcano (La Reunion Island) from tilt analysis at a single very broadband seismic
519 station. *Geophys. Res. Lett.* **41**, 2803-2811 (2014); published online EpubApr 28 (10.1002/2014GL059691).

520 46. A. Di Muro, N. Metrich, D. Vergani, M. Rosi, P. Armienti, T. Fougereux, E. Deloule, I. Arienzo, L. Civetta,
521 The Shallow Plumbing System of Piton de la Fournaise Volcano (La Reunion Island, Indian Ocean) Revealed
522 by the Major 2007 Caldera-Forming Eruption. *J. Petrol.* **55**, 1287-1315 (2014); published online EpubJul
523 (10.1093/petrology/egu025).

524 47. T. Kaneko, A. Yasuda, T. Shimano, S. Nakada, T. Fujii, T. Kanazawa, A. Nishizawa, Y. Matsumoto,
525 Submarine flank eruption preceding caldera subsidence during the 2000 eruption of Miyakejima Volcano,
526 Japan. *Bull. Volcanol.* **67**, 243-253 (2005); published online EpubMar (10.1007/s00445-004-0407-1).

527 48. M. Amma-Miyasaka, M. Nakagawa, S. Nakada, Magma plumbing system of the 2000 eruption of
528 Miyakejima Volcano, Japan. *Bull. Volcanol.* **67**, 254-267 (2005); published online EpubMar
529 (10.1007/s00445-004-0408-0).

530 49. T. Nishimura, S. Ozawa, M. Murakami, T. Sagiya, T. Tada, M. Kaidzu, M. Ukawa, Crustal Deformation
531 caused by magma migration in the northern Izu Islands, Japan. *Geophys. Res. Lett.* **28**, 3745-3748 (2001);
532 published online EpubOct 1 (Doi 10.1029/2001gl013051).

533 50. S. A. Fedotov, L. B. Slavina, S. L. Senyukov, M. S. Kuchay, Seismic processes and migration of magma
534 during the Great Tolbachik Fissure Eruption of 1975-1976 and Tolbachik Fissure Eruption of 2012-2013,
535 Kamchatka Peninsula. *Izv. Atmos. Ocean Phy.* **51**, 667-687 (2015); published online EpubDec
536 (10.1134/S000143381507004x).

537 51. S. A. Fedotov, I. S. Utkin, L. I. Utkina, The Peripheral Magma Chamber of Ploskii Tolbachik, a Kamchatka
538 Basaltic Volcano: Activity, Location and Depth, Dimensions, and their Changes Based on Magma Discharge
539 Observations. *J. Volcanol. Seismol.* **5**, 369-385 (2011); published online EpubDec
540 (10.1134/S0742046311060042).

541 52. P. Doubik, B. E. Hill, Magmatic and hydromagmatic conduit development during the 1975 Tolbachik
542 Eruption, Kamchatka, with implications for hazards assessment at Yucca Mountain, NV. *J. Volcanol.*
543 *Geotherm. Res.* **91**, 43-64 (1999); published online EpubJul (Doi 10.1016/S0377-0273(99)00052-9).

544 53. S.A. Fedotov, A. M. Chirkov, N.A. Gusev, G. N. Kovalev, Y. B. Slezin, The large fissure eruption in the
545 region of Plosky Tolbachik volcano in Kamchatka, 1975–1976. *Bull. Volcanol.* **43**, 47-60 (1980).

546 54. J. Filson, T. Simkin, L. K. Leu, Seismicity of a caldera collapse: Galapagos Islands 1968. *J. Geophys. Res.*,
547 **78**(35), 8591-8622 (1973).

548 55. J. E. Hammer, M. J. Rutherford, W. Hildreth, Magma storage prior to the 1912 eruption at Novarupta,
549 Alaska. *Contrib. Mineral. Petr.* **144**, 144-162 (2002); published online EpubNov (10.1007/s00410-002-0393-
550 2).

551 56. M. J. Rutherford, J. D. Devine, in *Fire and Mud: Eruptions and Lahars of Mount Pinatubo, Philippines* C.
552 G. Newhall, R. S. Punongbayan, Eds. (Philippine Institute of Volcanology and Seismology & University of
553 Washington Press, Quezon City, Seattle & London, 1996), pp. 751–766.

554 57. H. Kanamori, J. Mori, E. Hauksson, T. H. Heaton, L. K. Hutton, L. M. Jones, Determination of earthquake
555 energy release and ML using TERRAScope. *Bull. . Seismol. Soc. Am.*, **83**(2), 330-346 (1993).

556 58. M. Kikuchi, Y. Yamanaka, K. Koketsu, Source Process of the Long-period Seismic Pulses Associated with
557 the 2000 Eruption of Miyakejima Volcano and its Implications. *J. Geograph. Tokyo* **110**(2), 204-216 (2001).

558 59. M. T. Gudmundsson, T. Hognadóttir, A. B. Kristinsson, S. Gudbjörnsson, Geothermal activity in the
559 subglacial Katla caldera, Iceland 1999-2005, studied with radar altimetry. *Ann. Glacio.* **45**, 66-72 (2007).

560 60. C. Mätzler, Microwave permittivity of dry snow. *IEEE Trans. Geosci. Remote Sens.* **34**, 573-581 (1996).

561 61. C. Rossi, C. Minet, T. Fritz, M. Eineder, R. Bamler, Temporal monitoring of subglacial volcanoes with
562 TanDEM-X—Application to the 2014–2015 eruption within the Bárðarbunga volcanic system, Iceland.
563 *Remote Sens. Environ.* **181**, 186-197 (2016)

564 62. T. Johannesson, H. Björnsson, E. Magnússon, S. Guðmundsson, F. Pálsson, O. Sigurðsson, T.
565 Thorsteinsson, E. Berthier, Ice-volume changes, bias estimation of mass-balance measurements and
566 changes in subglacial lakes derived by lidar mapping of the surface of Icelandic glaciers. *Ann. Glacio.* **54**, 63-
567 74 (2013).

568 63. E. Magnusson, F. Pálsson, H. Björnsson, S. Gudmundsson, Removing the ice cap of Oraefajökull central
569 volcano, SE-Iceland: Mapping and interpretation of bedrock topography, ice volumes, subglacial troughs
570 and implications for hazards assessments. *Jökull* **62**, 131-150 (2012).

571 64. H. Björnsson, F. Pálsson, M. T. Gudmundsson, *Vatnajökull, Northwest Part, 1:100 000: Bedrock*
572 *topography*, Landsvirkjun and Science Institute, University of Iceland, 1992.

573 65. A. H. Jarosch, Icetools: A full Stokes finite element model for glaciers. *Comput. Geosci.* **34**, 1004-1014
574 (2008).

575 66. J. W. Glen, The Creep of Polycrystalline Ice. *P. Roy. Soc. A-Math. Phy.* **228**, 519-538 (1955).

- 576 67. K. M. Cuffey, W. S. B. Paterson, *The Physics of Glaciers*. (Elsevier Butterworth-Heinemann, Burlington,
577 ed. 4, 2010).
- 578 68. C. E. Lesher, F. J. Spera, “Thermodynamic and Transport Properties of Silicate Melts and Magma” in *The*
579 *Encyclopedia of Volcanoes*, H. Sigurdsson, B. Houghton, H. Rymer, Eds. (Academic Press, Academic Press,
580 Heidelberg, Amsterdam, Boston, ed. 2, 2015), pp. 113-141.
- 581 69. R. Bödvarsson, S. T. Rögnvaldsson, R. Slunga, E. Kjartansson, The SIL data acquisition system—at present
582 and beyond year 2000. *Phys. Earth Planet. Inter.* **113**, 89-101 (1999).
- 583 70. R. Slunga, S. T. Rögnvaldsson, R. Bödvarsson, Absolute and relative locations of similar events with
584 application to microearthquakes in southern Iceland. *Geophys. J. Int.* **123**, 409–419 (1995).
- 585 71. S. Th. Rögnvaldsson, R. Slunga, Routine fault plane solutions for local networks: a test with synthetic
586 data. *Bull. Seism. Soc. Am.* **83**.4, 1232-1247 (1993).
- 587 72. R. Stefánsson, R. Bödvarsson, R. Slunga, P. Einarsson, S. Jakobsdóttir, H. Bungum, S. Gregersen, J.
588 Havskov, J. Hjelme, H. Korhonen, Earthquake prediction research in the South Iceland seismic zone and the
589 SIL project. *Bull. Seism. Soc. Am.* **83**, 696–716 (1993).
- 590 73. S., A., R. Cesca, T. Dahm, Discrimination of induced seismicity by full moment tensor inversion and
591 decomposition. *J. Seismol.* **17**, 147-163 (2013).
- 592 74. P. A. Rosen, S. Hensley, I. R. Joughin, F. K. Li, S. N. Madsen, E. Rodriguez, R. M. Goldstein, Synthetic
593 aperture radar interferometry, presented at *Proceedings of the IEEE*, 2000 (unpublished).
- 594 75. B. Kampes, Delft Object-oriented Radar Interferometric Software: User’s Manual and Technical
595 Documentation v4.02, presented at *Delft Technical University*, 1999 (unpublished).
- 596 76. Y. Y. Kagan, 3-D rotation of double-couple earthquake sources. *Geophys. J. Int.* **106**, 709–716 (1991).
- 597 77. R. M. Goldstein, C. L. Werner, Radar interferogram filtering for geophysical applications. *Geophys. Res.*
598 *Lett.* **25**, 4035-4038 (1998).
- 599 78. C. W. Chen, H. A. Zebker, Two-dimensional phase unwrapping with use of statistical models for cost
600 functions in nonlinear optimization. *J. Opt. Soc. Am. A Opt. Image. Sci. Vis.* **18**, 338-351 (2001).
- 601 79. Y. Okada, Internal deformation due to shear and tensile faults in a half-space. *B. Seismol. Soc. Am.* **82**,
602 1018-1040 (1992).
- 603 80. A. Hooper, J. Pietrzak, W. Simons, H. Cui, R. Riva, M. Naeije, A. Terwisscha van Scheltinga, E. Schrama, G.
604 Stelling, A. Socquet, Importance of horizontal seafloor motion on tsunami height for the 2011 Mw=9.0
605 Tohoku-Oki earthquake. *Earth Planet. Sc. Lett.* **361**, 469-479 (2013).
- 606 81. C. E. Ford, D. G. Russell, J. A. Craven, M. R. Fisk, Olivine-liquid equilibria: Temperature, pressure and
607 composition dependence of the crystal/liquid cation partition coefficients for Mg, Fe²⁺, Ca and Mn. *J.*
608 *Petrol.* **24**, 256-266 (1983).
- 609 82. H. J. Yang, R. J. Kinzler, T. L. Grove, Experiments and models of anhydrous, basaltic olivine-plagioclase-
610 augite saturated melts from 0.001 to 10 kbar. *Contrib. Mineral. Petr.* **124**, 1-18 (1996).

611 83. G. H. Gudfinnsson, D. C. Presnall, A pressure-independent geothermometer for primitive mantle melts.
612 *J. Geophys. Res.* **106**, B8 (2001).

613 84. K. D. Putirka, Thermometers and barometers for volcanic systems. *Rev. Mineral. Geochem.* **69**, 61-120
614 (2008).

615 85. Y. Kawakami, J. Yamamoto, H. Kagi, Microraman densimeter for CO₂ inclusions in mantle derived
616 minerals. *Appl. Spectrosc.* **57**, 1333-1339 (2003).

617 86. M.R. Burton, P. Allard, F. Mure, A. La Spina, Magmatic gas composition reveals the
618 source depth of slug-driven Strombolian explosive activity, *Science*, **317**, 5835, 227-230 (2007),
619 doi:10.1126/science.1141900.

620
621 87. A. Aiuppa, C. Federico, G. Giudice, S. Gurrieri, Chemical mapping of a fumarolic field: La Fossa Crater,
622 Vulcano Island (Aeolian Islands, Italy), *Geophys. Res. Lett.*, **32** (13) (2005), p. L13309
623 <http://dx.doi.org/10.1029/2005GL023207>

624 88. P.-J. Gauthier, O. Sigmarsson, M. Gouhier, B. Haddadi, and S. Moune, Elevated gas flux and trace metal
625 degassing from the 2014–2015 fissure eruption at the Bárðarbunga volcanic system, Iceland, *J. Geophys.*
626 *Res. Solid Earth*, **121**, (2016) doi:10.1002/2015JB012111.

627 89. E. Bali, O. Sigmarsson, S. Jakobsson, H. Gunnarsson, Volatile budget of the Nornahraun eruption in the
628 Bárðarbunga system, Iceland. Geophysical Research Abstracts Vol. 17, EGU2015-5757, 2015 EGU General
629 Assembly (2015). <http://meetingorganizer.copernicus.org/EGU2015/EGU2015-5757.pdf>

630 90. A. Burgisser, M. Alletti, B. Scaillet, Simulating the behavior of volatiles belonging to the C–O–H–S
631 system in silicate melts under magmatic conditions with the software D-Compress, *Comput. Geosci.*, **79**, 1–
632 14.

633 91. D. O. Potyondy, P. A. Cundall, A bonded particle model for rock. *Int. J. Rock Mech. Min.* **41**, 1329-1364
634 (2004).

635 92. D. Mas Ivars, M. E. Pierce, C. Darcel, J. Reyes-Montes, D. O. Potyondy, R. P. Young, P. A. Cundall, The
636 synthetic rock mass approach for jointed rock mass modelling. *Int. J. Rock Mech. Min.* **48**, 219-244 (2011).

637 93. Itasca Consulting Group, Inc. *PFC2D - Particle Flow Code in Two-Dimensions, Ver. 5.0.* Minneapolis,
638 Itasca (2014).

639 94. K. Mogi, Relations between the eruptions of various volcanoes and the deformations of the ground
640 surfaces around them. *B. Earthq. Res. Inst. Univ. Tokyo* **36**, 99–134 (1958).

641 95. M. Ripepe, D. Delle Donne, R. Genco, G. Maggio, M. Pistolesi, E. Marchetti, G. Lacanna, G. U. P. Poggi,
642 Volcano seismicity and ground deformation unveil the gravity-driven magma discharge dynamics of a
643 volcanic eruption. *Nat. Commun.* **6** (2015).

644 96. Y. Bottinga, D. Weill, The viscosity of magmatic silicate liquids: a model for calculation. *Am. J. Sci.* **272**,
645 438–475 (1972).

646

647 **One page summary:**

648 **Gradual caldera collapse at Bárðarbunga volcano, Iceland,**
649 **regulated by lateral magma outflow**

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661 **INTRODUCTION:** The Bárðarbunga caldera volcano in central Iceland collapsed from August
662 2014 – February 2015 during the largest eruption in Europe since 1784. An ice-filled subsidence
663 bowl 8 x 11 km wide and up to 65 m deep developed, while magma drained laterally for 45 km
664 along a subterranean path and erupted as a major lava flow northeast of the volcano. Our data
665 provide unprecedented insight into the workings of a collapsing caldera.

666 **RATIONALE:** Collapses of caldera volcanoes are, fortunately, not very frequent, as they are often
667 associated with very large volcanic eruptions. On the other hand, the rarity of caldera collapses
668 limits insight into this major geological hazard. Since the formation of Katmai caldera in 1912,
669 during the 20th century's largest eruption, only five caldera collapses are known to have occurred

670 before that at Bárdarbunga. We used aircraft-based altimetry, satellite photogrammetry, radar
671 interferometry, ground-based GPS, evolution of seismicity, radio-echo soundings of ice thickness,
672 ice flow modeling and geobarometry to describe and analyze the evolving subsidence geometry, its
673 underlying cause, the amount of magma erupted, the geometry of the subsurface caldera ring faults
674 and the moment tensor solutions of the collapse-related earthquakes.

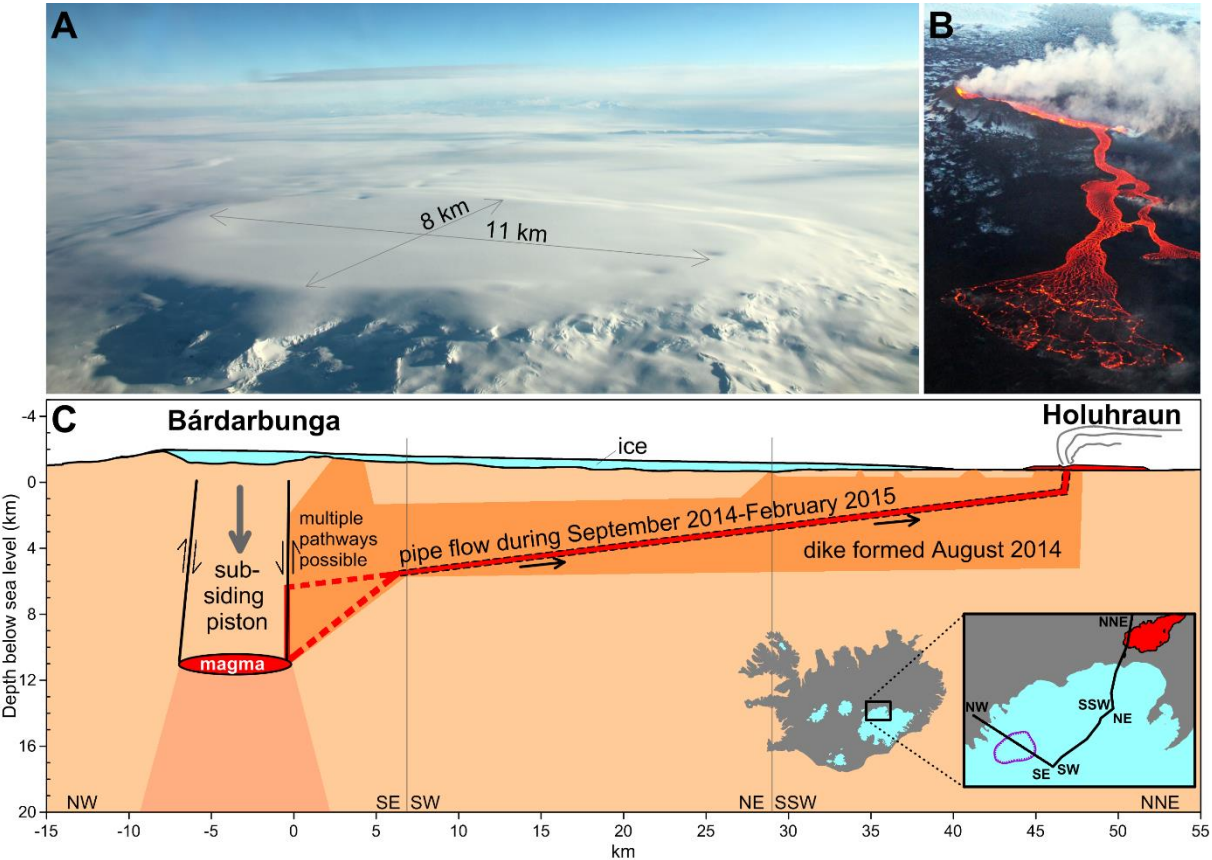
675 **RESULTS:** After initial lateral withdrawal of magma for some days though a magma-filled
676 fracture propagating through the Earth's upper crust, pre-existing ring faults under the volcano were
677 reactivated over the period 20-24 August, marking the onset of collapse. On August 31, the eruption
678 started and it terminated when the collapse stopped, having produced 1.5 km³ of basaltic lava. The
679 subsidence of the caldera declined with time in a near exponential manner, in phase with the lava
680 flow rate.

681 The volume of the subsidence bowl was about 1.8 km³. Using radio-echo soundings, we find that
682 the subglacial bedrock surface after the collapse is down-sagged with no indications of steep fault
683 escarpments. Using geobarometry, we determined the source depth of the magma to be
684 approximately 12 km and modelling of geodetic observations gives a similar result. High precision
685 earthquake locations and moment tensor analysis of the remarkable magnitude M5 earthquake
686 series are consistent with steeply dipping ring faults. Statistical analysis of seismicity reveals
687 communication over tens of kilometers between the caldera and the dyke.

688 **CONCLUSIONS:** We conclude that interaction between the pressure exerted by the subsiding
689 reservoir roof and the physical properties of the subsurface flow path explain the gradual near
690 exponential decline of both collapse rate and the intensity of the 181-day long eruption. By
691 combining our various data sets, we show that the onset of collapse was caused by outflow of
692 magma from underneath the caldera when 12-20% of the total magma intruded and erupted had
693 flowed from the magma reservoir. However, the continued subsidence was driven by a feedback
694 between the pressure of the piston-like block overlying the reservoir, and the 47 km long magma

695 outflow path. Our data provide better constraints on caldera mechanisms than previously available,
 696 demonstrating what caused the onset, and how both the roof overburden and the flow path
 697 properties regulate the collapse.

698



699

700 **The Bárðarbunga caldera and the lateral magma flowpath to the Holuhraun eruption site.**
 701 (A) Aerial view of the ice-filled Bárðarbunga caldera on 24 October 2014, view from the north. (B)
 702 The effusive eruption in Holuhraun, 45 km to the northeast of the caldera. (C) A schematic cross-
 703 section through the caldera and along the lateral subterranean flow path between the magma
 704 reservoir and the surface.

705



Supplementary Materials for

Gradual Caldera Collapse at Bárðarbunga Volcano, Iceland, Regulated by Lateral Magma Outflow

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This PDF file includes:

Materials and Methods

SupplementaryText

Figs. S1 to S8

732 **Materials and Methods**

733 Mapping of collapse

734 Ice surface topography was mapped 18 times in the period September 5, 2014 to June 4, 2015 (Fig. S1). An
735 aircraft-based system (59) of sub-meter differential GPS and ground clearance altimeter (4.3 GHz wave,
736 vertical elevation accuracy ± 2 m) on board the survey aircraft of Isavia, the Icelandic Civil Aviation Service
737 (59) provided 13 maps (Marked as FMS on Fig. S1). Survey lines were flown at 70-120 m ground clearance,
738 measuring 4 times/sec. (at ~ 15 m intervals), and included coverage of the growing geothermal ice
739 cauldrons. Comparison with kinematic GPS ground surveys in November, February and June (accuracy ± 0.3
740 m), as well as snow temperature models and measurements show that the reflecting surface was
741 unaffected by accumulation of winter snow and remained at the September 2014 summer surface until
742 October, after which it gradually migrated downwards to ~ 1.5 m below it by February 2015. The reflecting
743 surface probably indicates the lower boundary of the dry snow layer where snow temperature was $< 0^\circ\text{C}$
744 (60). A subset of this data was used by Rossi et al. (61) to compare with Tandem-X derived maps of the
745 subsidence for specific dates in late 2014. Optical photogrammetry maps were made using satellite data
746 for August 28 (Spot 6 satellite), September 20 and October 10 (Pléiades satellite). Combined, the surface
747 data provide a record of collapse volume with time (Fig. 3B). The curve in Fig. 3B is drawn using the
748 difference of the running average of volume obtained in three adjacent surveys. The rate of volume change
749 obtained in this way is also used in Fig. 6B. A continuously recording GPS station (BARC) was installed on
750 the ice-surface on September 12, 2014. This station monitored the subsidence continuously for a large part
751 of the unrest, although snow covering the antenna lead to some data gaps. A detailed ground kinematic
752 GPS survey within and around the caldera on June 3-10, 2015 allowed the margins of collapse to be
753 determined. Measurements of winter accumulation in the Bárdarbunga caldera in June 2015 constrained
754 subsidence data while a glacier surface lidar map from 2011-2012 (62) was used as reference surface.

755

756 Radio-echo soundings (RES)

757 On February 3, 2015, when over 95% of the subsidence had occurred, 45 km of RES-profiles (1-5 MHz
758 receiver bandwidth) were measured in over-snow traverses, covering about 2/3 of the caldera floor,
759 including a large part of the subsided area. Bedrock echoes were detected for $\sim 90\%$ of the measurements.
760 Along-profile bedrock echoes in length-depth coordinates were migrated (63) to compensate for the width
761 of the radar beam (~ 200 m). Comparison of our data with previous mapping done in 1985 (64) indicates
762 that the over 60 m subsidence had not caused significant changes in ice thickness; the maximum thickness
763 observed is close to 800 meters on both occasions.

764

765 Ice flow modelling

766 Assuming no basal slip ($\mathbf{v}_b = 0$), ice deformation within the caldera has been computed using a Full-Stokes
767 finite element model solving the standard equations (65). On the lateral boundaries of the model domain,
768 no flow conditions (i.e. $\mathbf{v} = 0$) have been defined and the model domain chosen to be sufficiently large so
769 that the lateral boundary conditions do not influence the ice flow within the caldera. The rate factor in
770 Glen's flow law (66) has been estimated by constraining the horizontal model surface velocities to fit the
771 measured ones at the BARC GPS station for the period September 12 to February 3. This yielded $A = 1.6 \cdot 10^{-24}$
772 $\text{Pa}^{-3}\text{s}^{-1}$ assuming the nonlinearity parameter in Glen's flow law to be $n=3$. This is somewhat stiffer than
773 textbook values for temperate ice ($A = 2.4 \cdot 10^{-24} \text{ Pa}^{-3}\text{s}^{-1}$, ref. 67) but is to be expected in a volcanic setting

774 where the ice body contains several tephra layers. Moreover, this low value for A supports our initial
775 assumption of no basal slip. At the basal boundary, the post-collapse bed topography from the RES survey
776 has been used and the surface of each model utilized the respective surface DTM implemented as a free
777 surface within the FEM model. The ice flow modelling (Fig. S2) indicates that the ice surface subsidence was
778 almost identical to bedrock subsidence everywhere in the caldera (error <1 m) in September-October.
779 However, by the end of February the inflow of ice towards the bottom of the subsidence structure had
780 resulted in uplift of about 3 m in the center and a subsidence of 1-3 m on a circle around the uplifted
781 central part.

782

783 Lava volume and flow rate

784 The surface elevation of the growing Holuhraun lava flow was measured using a Theodolite from the
785 ground in September 21 2014, and with the Isavia aircraft (see above on mapping of collapse) on November
786 4 and 26, December 4 and 30 and January 21, as well as later surveys in 2015. The aircraft surveys were
787 calibrated with kinematic GPS profiling of the surface. These data give lava volumes at the time of survey,
788 providing estimates of the average magma flow rate over periods of some weeks (Fig. 6B) and a final lava
789 volume of $1.5 \pm 0.2 \text{ km}^3$. Nettleton gravity profiles obtained in September 2015 of the lava indicate average
790 bulk lava density of $2500 \pm 100 \text{ kg m}^{-3}$. Using a basaltic magma density of 2750 kg m^{-3} for pressure of 300-400
791 MPa (68) the equivalent volume of magma at ~12 km depth in the crust is $1.4 \pm 0.2 \text{ km}^3$.

792

793 Relative locations of microearthquakes

794 $M \leq 2$ earthquakes at the caldera recorded at distances <100 km between August 1 and October 17 by the
795 Icelandic national seismic network, SIL (69) were relatively relocated using a standard 1D velocity model
796 (70). SIL magnitudes were calculated according to Rognvaldsson and Slunga (71). A double-difference
797 method was used, where absolute and relative arrival times of P and S waves determined through cross-
798 correlation of waveforms, were inverted for best locations in multiple overlapping groups (72). Depth is set
799 to zero at bedrock caldera floor (1.2 km above sea level, see Figs. 5 and 6). The relocated events roughly
800 follow the north and south caldera rims; mostly being outside the northern rim and ~1 km inside the
801 southern rim (Fig. 5A-B). Stability tests of relocations with subsets of events and stations indicated
802 perturbations to event latitudes, particularly on the northern rim, probably due to slow velocities inside the
803 caldera.

804 The InSAR detected subsidence associated with a M5.3 event on 18 September places the surface fault at
805 ~2.5 km inside the pre-existing topographic northern caldera rim (Fig. S7), while the seismic epicentre
806 location is just north of the northern caldera rim. Using the InSAR observation to locate the surface
807 expression for the steeply outwards dipping caldera fault, the microearthquakes were shifted southward
808 according to: $\text{New lat} = \text{old lat} * 0.883 + 7.552$. The shifted locations are used in Figure 5. The shift is of the
809 same order as the absolute error in the hypocentre locations. However, besides fitting the hypocentres to
810 the InSAR-located fault it provides more consistency to S-P times from 82 events observed on an
811 accelerometer at location BARC (Fig1A) from November 2014 to February 2015.

812

813 Moment tensor inversion and classification

814 The steady subsidence of the caldera was accompanied by a sequence of episodic $M > 5$ earthquakes, which
815 excited low frequency signals recorded at regional distances throughout Iceland. We performed a regional
816 moment tensor inversion for all events with $M > 5$, adopting a full moment tensor (MT) point source
817 approximation, neglecting higher order moment tensor. The MT inversion (73) was performed by fitting full
818 waveforms 3-component displacements at regional distances (40-200 km), in the low frequency band 0.01-
819 0.05 Hz. We obtain centroid location, centroid depth and full MT solutions for 77 earthquakes at the
820 caldera and with $M > 5$. MTs were decomposed into double couple (DC), compensated linear vector dipole
821 (CLVD) and isotropic (ISO) components. Since MTs mostly differ in their DC components, we classified upon
822 the similarity of the DC orientation using a clustering algorithm (73) and the normalized Kagan angle (74) as
823 norm.

824

825 Waveform similarity analysis and moment estimation

826 To extend the interpretation of source processes to smaller events, where MT inversion becomes less
827 stable, we apply a waveform similarity analysis. The scaling of the low frequency signals of weaker events
828 and larger ones with similar waveforms is used to infer the scalar moment of smaller events ($M < 5$) from
829 the known moment of the larger ones, resulting from the MT inversion procedure. In this way, we are able
830 to estimate scalar moments for more than 600 events (352 with $M_w > 4.0$), down to a magnitude of M_w
831 3.3. These results allow tracking of the details of the temporal evolution of the moment release.

832

833 Mechanism corrected relative location

834 Moment tensor inversion provides a first estimate of centroid location and depth. A more precise location
835 can be obtained by using relative location techniques, here also favored by the high waveform similarity.
836 However, waveform-based lag-times can be affected by the dissimilarity among waveforms for the two
837 families of events. To overcome this problem, we corrected cross-correlation lag times, by using corrections
838 based upon focal mechanisms. The adopted procedure includes the computation of synthetic seismograms
839 for different observed source mechanisms, the cross-correlation of synthetic waveforms to estimate
840 fictitious time lags due to different focal mechanisms, and the inference of a time lag correction for each
841 possible focal mechanism pair. As a result, we improved epicentral locations for 227 events. In order to
842 obtain absolute locations, we combine the relative centroid locations of the largest events with the new
843 absolute epicentral locations, imposing the condition that the mean centroid locations correspond to the
844 mean absolute locations for both the northern and the southern cluster.

845

846 Caldera-dike seismicity correlations

847 The histogram shown in Figure 6A is computed using a simple model using the number of dyke
848 earthquakes in 1.5 hour bins before and after (i) $4 < M < 4.6$ and (ii) $M > 4.6$ caldera earthquakes (61). For
849 example, the height of the fourth bar is found by assuming that the rate of dyke earthquakes during the 1.5
850 hours immediately preceding an $M \geq 4.6$ caldera earthquake is α times the reference rate, and estimating α
851 with maximum likelihood, giving $\alpha = 1.96$. The plot can be read as, for example, the expected rate of dyke
852 earthquakes is increased by 96% in the time interval 1.5 hours before an $M \geq 4.6$ caldera earthquake.

853 P-values are computed with a likelihood ratio test, and the confidence intervals are likelihood based. The
854 reference rate (equal to 1 in Fig. 6A) is the rate of earthquake occurrence in periods more than three hours
855 before or after caldera earthquakes of size $M > 4$. All dyke earthquakes that fall in one of the bins of Figure
856 6A together with all the dyke earthquakes in the reference periods are considered. The null hypothesis is
857 that the portion of these earthquakes that fall in the bin is binomially distributed with parameter
858 corresponding to a constant reference rate. To minimize the effect of the varying reference rate between
859 months, the model assumes that this holds for each calendar month, and the final likelihood used in the
860 test is the product of the likelihoods of individual months.

861

862

863 GPS analysis

864 The high-resolution GPS time series at BARC in the center of the caldera (Fig. 3C) was obtained using RTKLIB
865 software, processing the receiver locations every 15 seconds as kinematic baselines from the HOFN
866 reference station in southeast Iceland. Other GPS data were analyzed using the GAMIT/GLOBK software,
867 version 10.6 using over 100 global reference stations to evaluate site positions in the ITRF08 reference
868 frame. For the regional network average daily station positions were estimated. For the caldera GPS station
869 (BARC) we furthermore divided the data into eight hour sessions using a 24 hour running window of
870 reference station and orbit data. In the processing we solve for station coordinates, satellite orbit and earth
871 rotation parameters, atmospheric zenith delay every two hours, and three atmospheric gradients per day.
872 The IGS08 azimuth and elevation dependent absolute phase center offsets were applied to all antennas and
873 ocean loading was corrected for using the FES2004 model.

874

875 InSAR analysis

876 We utilized X-band (wavelength 3.11 cm) radar images acquired by the COSMO-SkyMed constellation and
877 employed two-pass Interferometric Synthetic Aperture Radar (InSAR) analysis (75) to measure ground
878 deformation at Bárðarbunga caldera over 24-hr periods during which large caldera earthquakes occurred.
879 The interferograms were processed using DORIS software (76) and a merged LiDAR, intermediate TanDEM-
880 X, ASTER and EMISAR DEM was used to remove topographic fringes (77). To account for the large changes
881 in topography over the caldera during the eruption, we interpolated the digital elevation model, using data
882 from the continuous GPS station located inside the caldera. The wrapped interferometric phase values
883 were filtered using an adaptive filter (78) and unwrapped with SNAPHU software (79). The one-day
884 interferogram spanning September 17-18, 2014 was used to infer the location of faults that slipped during
885 this period, which included a large caldera ($M_{5.3}$) earthquake (Fig. S7). We modelled the fault system as a
886 series of 30 rectangular vertical faults (79) with varying strike, and estimated location, size, minimum depth
887 beneath the surface, and slip for each segment. Note, the data could be fitted equally well with steeply
888 dipping faults, in either direction, but we fixed them to be vertical for convenience. The southern margin
889 did not slip in this 24-hour interval and the model therefore does not constrain the actual location of the
890 southern caldera fault. The contracting body at the base of the fault system was also modelled as a closing
891 rectangular dislocation with uniform contraction (79). We used a Markov-chain Monte Carlo approach to
892 estimate the multivariate probability distribution for all model parameters (80).

893

894 Petrological analysis and thermobarometry

895 Major element compositions of minerals and glasses were analyzed using a JEOL JXA-8230 electron
896 microprobe at the Institute of Earth Sciences, University of Iceland. Fluid inclusions within phenocrysts
897 were analysed by optical microscopy and confocal Raman spectroscopy (Horiba Jobin Yvon LabRAM HR800)
898 at the Bayerisches Geoinstitut, Bayreuth, Germany. Eruption temperatures calculated with different
899 thermometers (81-83) for the erupted lava are consistently in the range 1165-1180°C, in good agreement
900 with on-site measurements by thermal imaging cameras. Three independent thermobarometers were used
901 to constrain the depth of magma accumulation before the onset of the eruption; (i) *Glass thermobarometry*
902 was carried out using the fractional crystallization model of Yang et al. (82), which was calibrated using
903 basaltic melt compositions, (ii) *Clinopyroxene-Liquid Thermobarometry* was carried out based on the
904 clinopyroxene-liquid barometers published by Putirka (84) that rely on the pressure and temperature
905 dependence of Fe, Mg, Al and Na partitioning between pyroxenes and coexisting melt, and (iii) *CO₂ Density*
906 *Barometry* which is based on the principle that distance between the two Raman bands of CO₂ (in the
907 wavenumber region between 1250 and 1450 cm⁻¹) is a function of fluid density (85). In combination with
908 information on the temperature of the system, the entrapment pressure can be estimated based on the
909 equation of state of CO₂.

910

911 Subaerial gas composition analysis

912 The composition of the subaerial eruptive gases was measured by open-path Fourier Transform Infrared
913 spectrometer (FTIR) (86) on September 3, 19, 20 and 21 using the erupting lava as an infrared radiation
914 source, and Multi-Component Gas Analyzer System (MultiGAS) (87) on September 1, 21, October 8, January
915 26 and February 6. The MultiGAS measurements were taken downwind from vent when the plume was
916 grounded. Major element composition and wt% of volatiles of the melt were defined using the average of
917 four clinopyroxene-hosted melt inclusions (88, 89) and used as input to the D-COMPRESS magma/volatile
918 partition software (90). The model was run from atmospheric pressure to 600 MPa (18 km). The simulation
919 results indicate that the sulfur reaches 1600 ppm, the highest concentrations measured in melt inclusions
920 most representative of the pre-eruptive magma composition (88), at 470±100 MPa (14±3 km). This
921 estimate is partly dependent on the solubility constants provided for basalt. However, it convincingly
922 supports the petrological and geodetic estimates.

923

924 DEM modelling

925 We evaluated the role of pre-existing ring fault structures on the 2014-15 collapse by using the two-
926 dimensional Distinct Element Method (DEM) software PFC 5.0 (90). The DEM models comprise a 40 × 25 km
927 gravitationally-loaded assemblage of rigid circular particles that interact according to frictional-elastic
928 contact laws (91). Particles have a uniform size distribution, with radii between 60 m and 100 m, and a
929 density of 2700 kgm⁻³. The model's basal and the lateral boundaries are frictionless rigid walls. Inter-particle
930 and particle-wall contacts have a Young's modulus of 70 GPa and a normal to shear stiffness ratio of 2.5.
931 The model comprises three regions (Fig. 5D): (i) A laccolith-like 'magma reservoir'. (ii) A fault-bound
932 reservoir 'roof'. (iii) The 'host rock' around the reservoir and roof. Within the reservoir, the contact friction
933 is 0.01 and particles are not bonded. Outside the reservoir, the contact friction coefficient is 0.5 and
934 particles are bonded with linear elastic beams. Bond tensile and shear strengths are 35 MPa in the roof and
935 70 MPa in the surrounding host rock. Note that fracturing of the weaker 'roof' zone will reduce the

assembly-scale strength and modulus here, locally by up to an order of magnitude (27), as suggested for Bardabunga by Riel et al. (32). Pre-existing faults, extending from the lateral edges of the reservoir to a few kilometres below the surface (Fig. 5D), are modelled by using a contact law for ‘smooth’ discontinuities in poly-disperse particle assemblages (92). The normal and shear stiffness of these ‘fault’ contacts is 60 GPa/m. Withdrawal of magma is assumed to occur laterally out of the 2D model plane (Fig. 5D) and is simulated by slowly reducing the areas of the reservoir particles. Displacements of surface particles were smoothed by a standard moving mean method to minimize localized particle effects. Our modelling comprised a series of forward simulations in which the dip of each fault was varied between 80-90 degrees, initial fault depths varied from 1-3 km, and chamber width varied from 7.0-8.5 km. Chamber depth was fixed at 12 km, based on the geobarometry data, to reduce the parameter space. The lateral position of the chamber was allowed to vary depending on the fault geometry, so that the faults lay within the clouds of hypocentres and projected upward to within the caldera. Effects of Young’s modulus, strength and fault friction were also systematically tested. Further details on DEM modelling of caldera collapse are given in Holohan et al. (27, 93).

950

951 Geodetic depth model

952 To determine the approximate depth of the magma chamber, we modelled post-rifting InSAR and GPS data
953 (Fig. S3) using a point pressure source in an elastic halfspace (94). The depth range at 95% confidence is 8-
954 12 km.

955

956

957 Coupled caldera subsidence and eruption model

958 We assume piston failure occurs approximately at a constant stress threshold, causing the pressure at the
959 top of magma chamber to remain constant on average. Therefore, we ignore compressibility and assume
960 that the density of the magma remains constant. The driving overpressure is then given by

961

$$962 \quad \Delta P = \frac{W-F}{A} + \rho gh - \rho gd \quad (1),$$

963

964 where W is the weight of the piston, F is the resistive force (friction), A is the cross sectional area of the
965 magma chamber, ρ is the density of the magma, g is gravitational acceleration, h is the height of magma
966 above the chamber exit point and d is the depth of the chamber exit point relative to the eruption site (Ext.
967 Data 7). Conservation of mass implies

968

$$969 \quad A \frac{dh}{dt} = -\pi r^2 v \quad (2),$$

970

971 where v is the mean magma flow speed and r is conduit radius. Assuming that the time-averaged resistive
 972 force due to friction, F , and d remain constant, differentiating (1) and substituting (2) gives

973

$$974 \quad \frac{d\Delta P}{dt} = -\rho g \frac{\pi r^2}{A} v \quad (3).$$

975

976 Assuming pressure loss due to viscous drag from laminar flow in a cylindrical pipe (Hagen Poiseuille flow)
 977 and dynamic pressure loss on exit

978

$$979 \quad \Delta P = \frac{8\eta L}{r^2} v + \frac{\rho}{2} v^2 \quad (4)$$

980

$$981 \quad \Rightarrow v = -\frac{8\eta L}{\rho r^2} + \sqrt{\left(\frac{8\eta L}{\rho r^2}\right)^2 + 2\frac{\Delta P}{\rho}} \quad (5).$$

982

983 We assume a cylindrical pipe, as models of thermal erosion predict that the cross section of a magma flow
 984 channel will evolve to be circular in shape, but note that for a non-circular cross section, the first term will
 985 still be proportional to the velocity, but with a different constant.

986

987 Expanding (5) gives

$$988 \quad \Rightarrow v = -\frac{8\eta L}{\rho r^2} + \frac{8\eta L}{\rho r^2} + \frac{r^2 \Delta P}{8\eta L} + O\left(\frac{r^2}{\eta L}\right)^2 = \frac{r^2 \Delta P}{8\eta L} + O\left(\frac{r^2}{\eta L}\right)^2 \quad (6).$$

989

990 Substituting (6) into (3) gives

991

$$992 \quad \frac{d\Delta P}{dt} = -\frac{\pi \rho g r^2}{A} \left[\frac{r^2 \Delta P}{8\eta L} + O\left(\frac{r^2}{\eta L}\right)^2 \right] \quad (7).$$

993

994 When $L \gg r^2$, this reduces to

995

$$996 \quad \frac{d\Delta P}{dt} = -\frac{\pi \rho g r^4}{8A\eta L} \Delta P \quad (8)$$

$$997 \quad \Rightarrow \Delta P = \Delta P_0 e^{-\frac{\pi \rho g r^4}{8A\eta L} t} \quad (9)$$

998

999 and

1000
$$h - h_{\infty} = (h_0 - h_{\infty})e^{-\frac{\pi \rho g r^4}{8 A \eta L} t} \quad (10).$$

1001

1002 A similar relationship has been derived to explain gravity-driven eruptions at Stromboli (95). Assuming that
1003 $h_0 - h_{\infty}$ is equal to the subsidence measured at the BARC GPS station, a best fit solution is $h_0 - h_{\infty} = 67.5$ m
1004 and $\frac{\pi \rho g r^4}{8 A \eta L} = 1.5 \times 10^{-7}$ (Fig. 3B). A similar fit is obtained for magma flow rate and caldera volume change in
1005 Fig. 6B. Substituting $\rho = 2700 \text{ kg m}^{-3}$ (ref. 64), $g = 9.8 \text{ ms}^{-2}$, $L = 47 \text{ km}$ and $\eta = 22 \text{ Pa s}$ using the average glass
1006 compositions of the Holuhraun lava (96), gives $\Delta P_0 = 1.7 \text{ MPa}$ and $\frac{r^4}{A} = 1.5 \times 10^{-5} \text{ m}^2$. Constraining the
1007 eruption rate to be $250 \text{ m}^3/\text{s}$ on 31 August, gives $A = 32 \text{ km}^2$ and $r = 4.7 \text{ m}$. This can be considered the
1008 effective radius of the flow path assuming circular cross sectional area. A similar relation would hold for
1009 other possible geometrical forms of the flow path cross sectional area. Theoretically, the eruption would
1010 approach equilibrium ($\Delta P = 0$ in (1)) asymptotically, but choking of the conduit due to cooling, slow-moving
1011 magma is expected before that.

1012

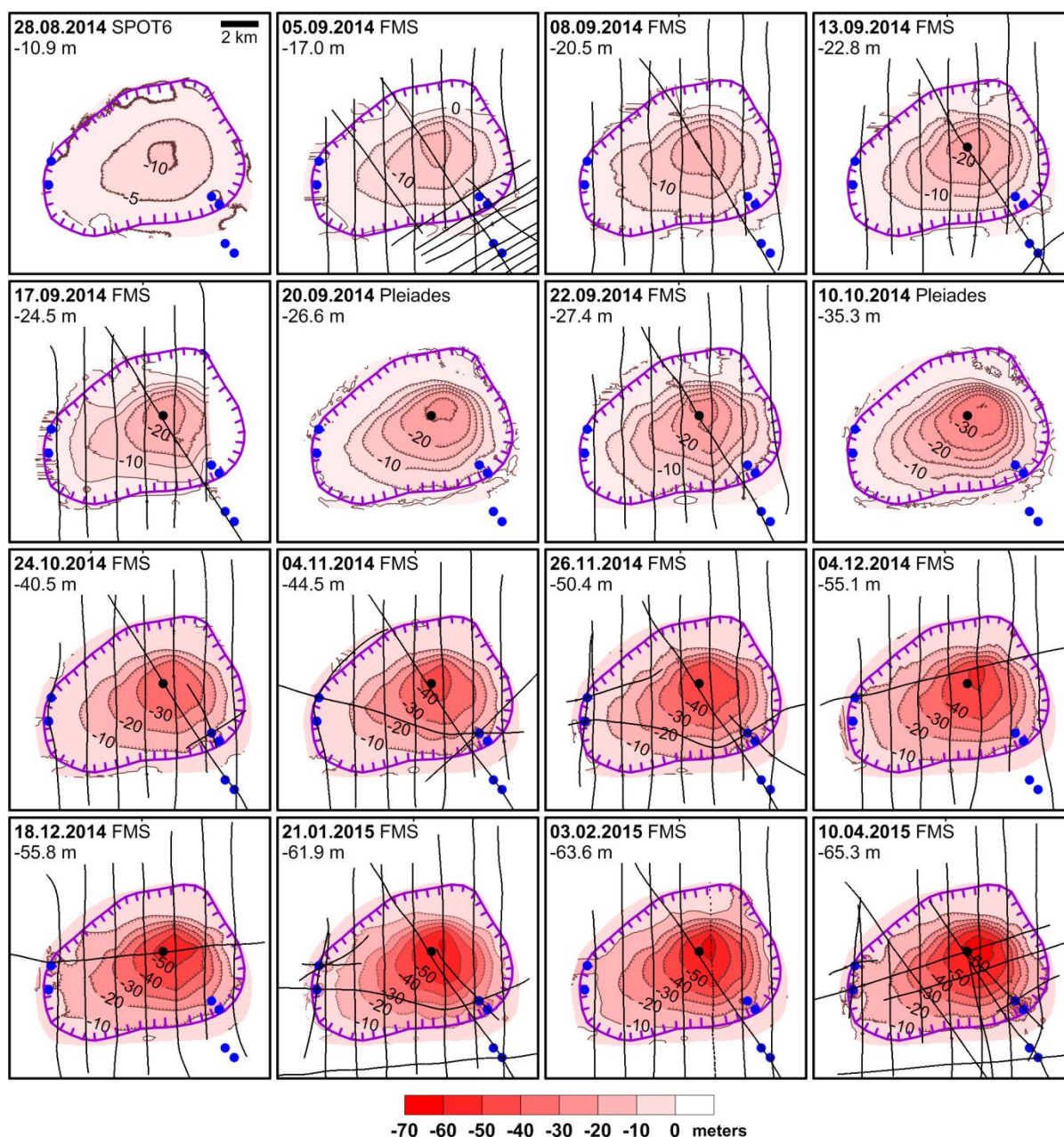


Fig. S1.

Maps of collapse – margins as in Fig. 1C. The maps are corrected for ice flow (Fig. S2) and migration of reflector into the autumn 2014 surface due to propagation of cold wave into the firn in October-April (24). The number underneath the date gives the maximum subsidence. Three maps are obtained through satellite photogrammetry (28.08 – Spot 6, 20.09 and 10.10 from Pléiades) while the remaining 13 maps (marked as FMS) are obtained using an aircraft-combining radar altimetry and a submeter Differential GPS; the maps are made by interpolation between the profiles (shown as black lines)(24).

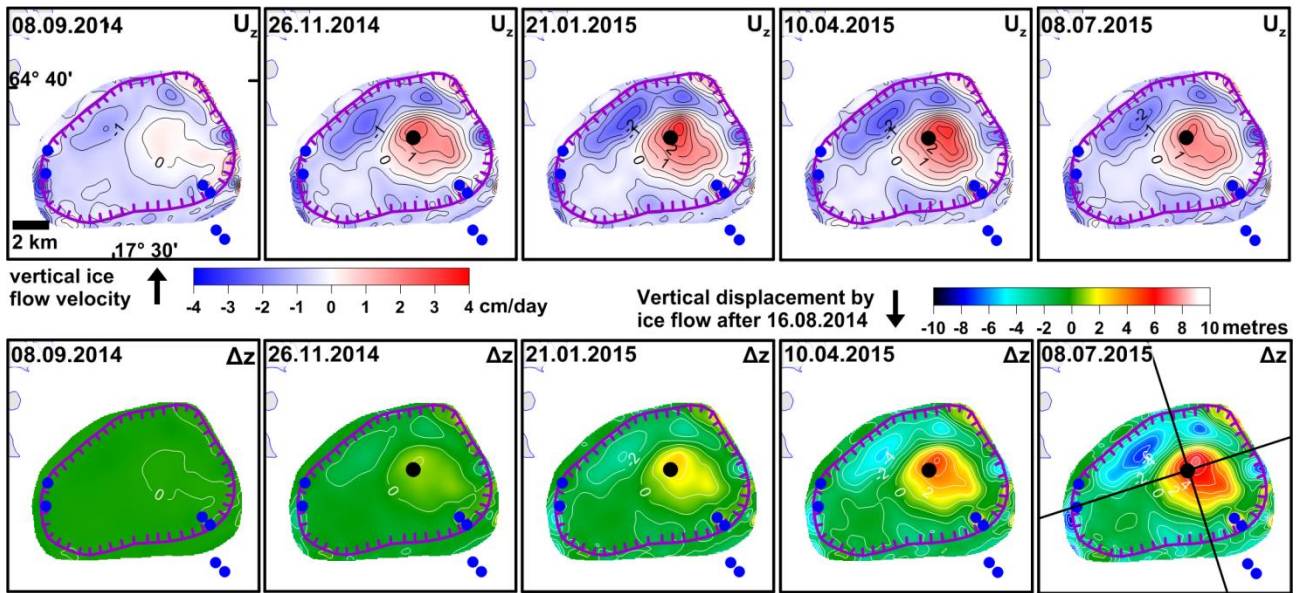


Fig. S2

Results of 3-D Full-Stokes ice flow models (see Materials and Methods) of the response of the glacier within the caldera to the subsidence for five dates spanning the period of collapse. The upper row shows vertical ice flow velocity while the lower row shows the accumulated surface elevation change due to the ice flow for the same dates. The model flow rates are constrained to fit the horizontal displacement of the GPS station BARC in the caldera center from September to February (see Materials and Methods). The maximum vertical ice flow velocity is modelled as having been about 3 cm per day on April 10, 2015. The accumulated uplift for end of eruption on February 27 (Fig. 1C) is obtained by interpolation between January 21 and April 10.

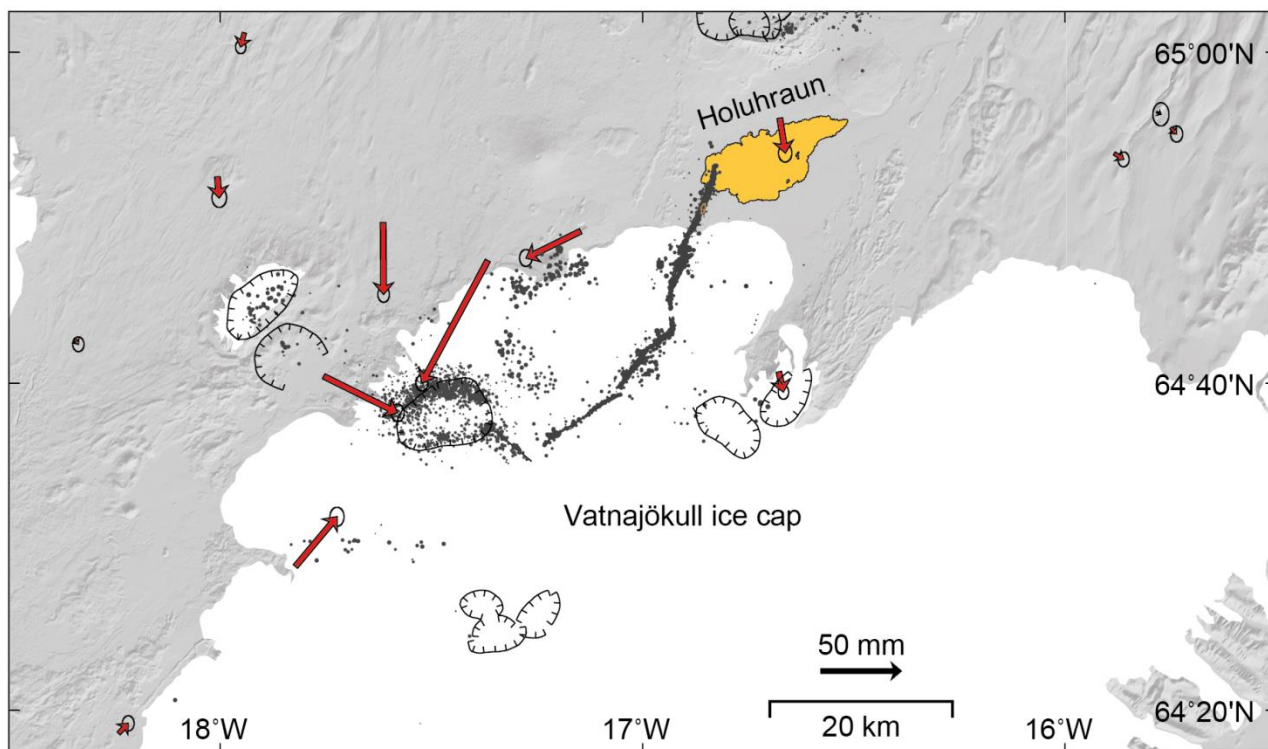


Fig. S3

GPS co-eruptive displacements, spanning September 21, 2014 until February 27, 2015, after the period of dyke opening had ended. The displacement field during the eruption shows consistent movements toward Bárðarbunga caldera suggesting deflation below the caldera. No other major deformation source can be observed during the eruption that can account for significant volume changes. Dots show relatively located earthquakes (20, 24).

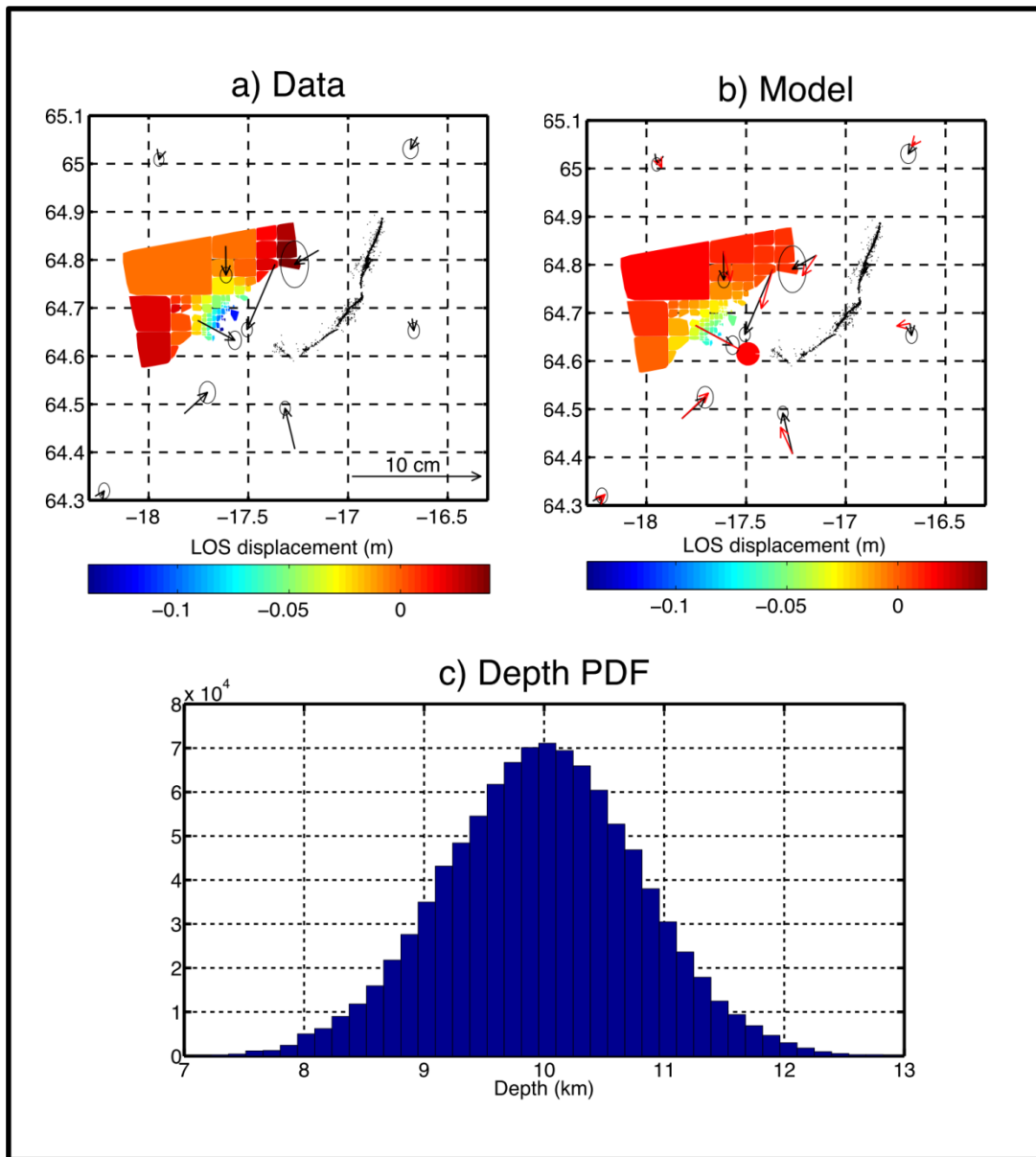


Fig. S4

Geodetic model of regional deformation using a contracting point pressure source. The upper panel from left to right displays the input data (a) and model (b). GPS data in both panels and the CSK ascending interferogram in (a) span the period September 16 to November 7, 2014. The red circle in (b) shows the location of the point pressure source. The black dots represent the seismicity in the vicinity of the dike. The black lines are the inferred dike location. The lower figure (C) displays the probability distribution for depth of the point source from 1 million iterations, using a Markov chain Monte Carlo approach.

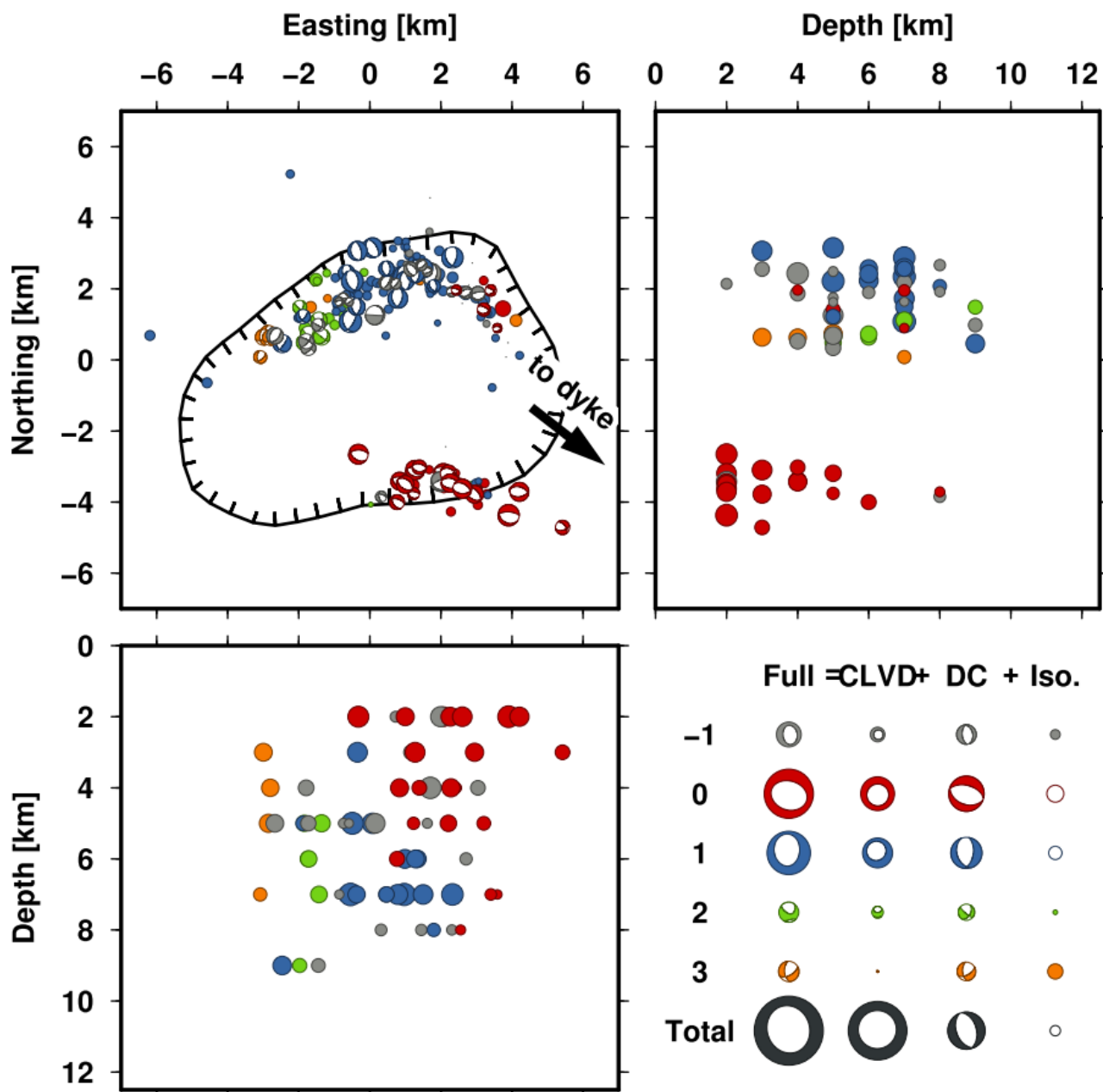


Fig. S5

Source mechanisms of 77 $M > 5$ events. Double couple (DC) components of the retrieved moment tensors (top left) and centroid locations for different cross sections (top right, bottom left). Focal mechanisms are colored according to the result of a DC clustering. The two main clusters are the red cluster, with a WNW-ESE normal faulting component, dominant at the southern rim; and the blue cluster, with N-S oriented normal faulting, characteristic of the northern rim. The standard decomposition is given in the bottom right panel for the four clusters, un-clustered (grey) and cumulative MTs (black).

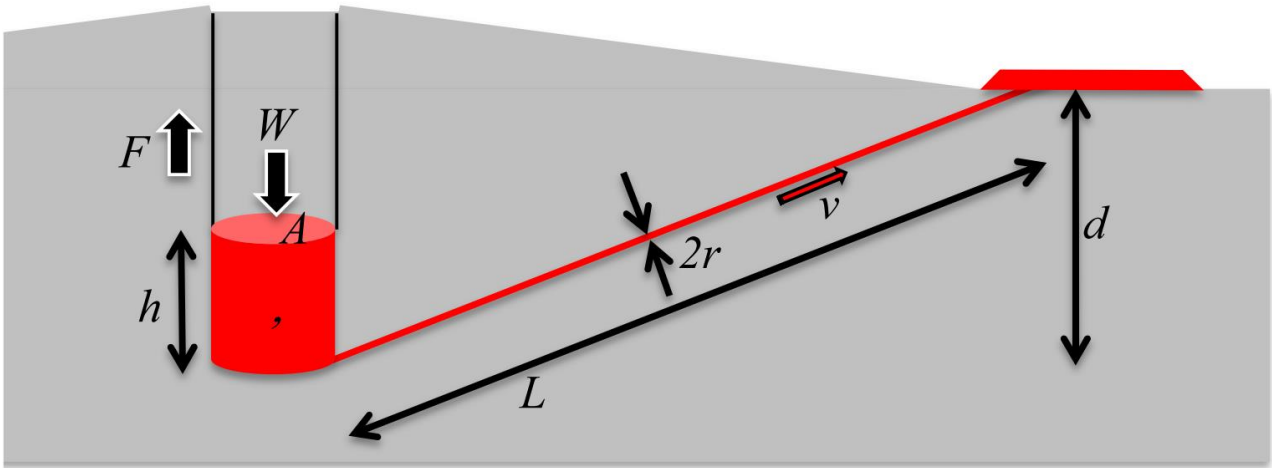


Fig. S6

Schematic of “piston collapse” model. Symbols as described in Materials and Methods

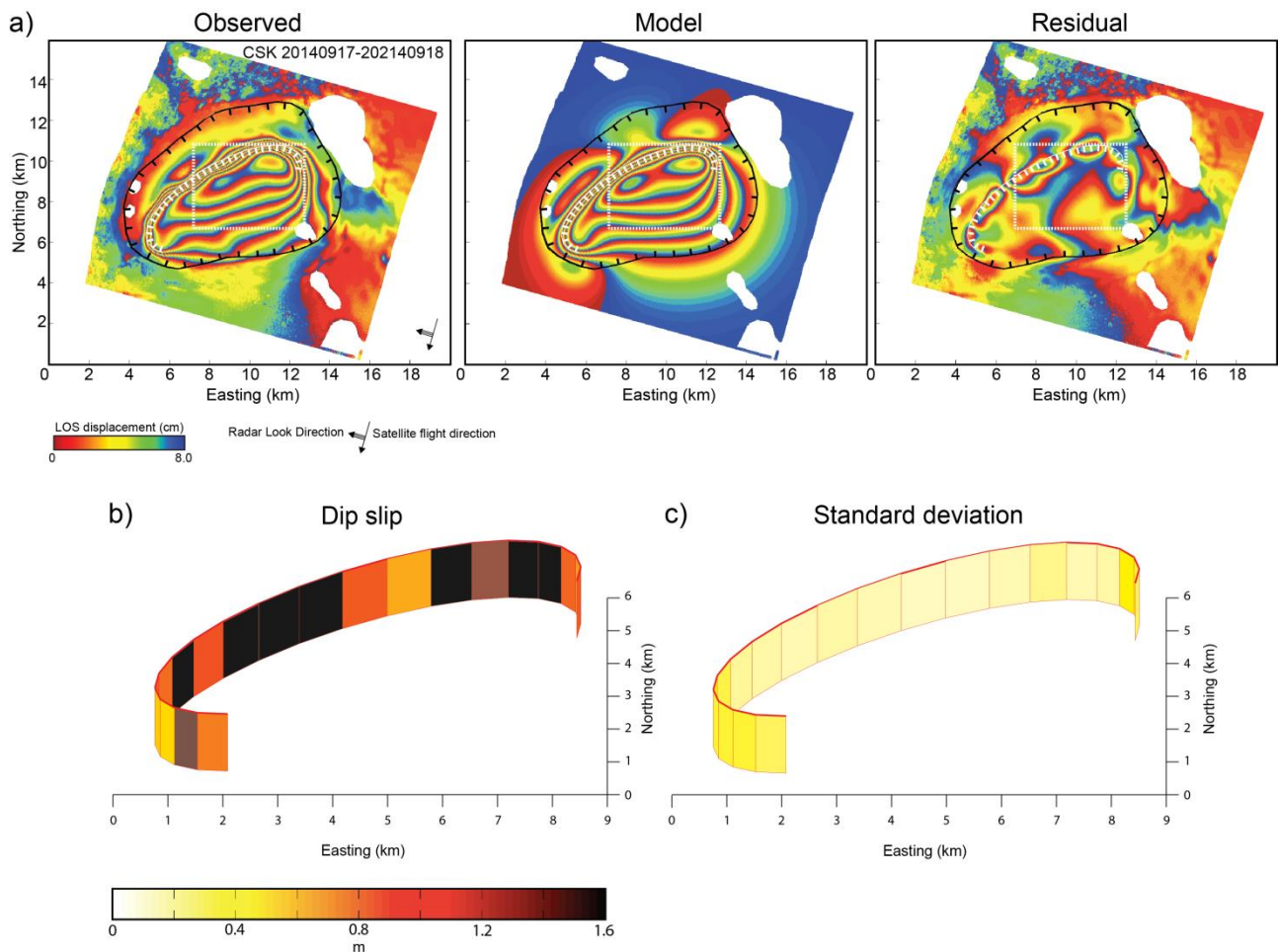


Fig. S7

Fault model for one-day interferogram. The data were acquired by COSMO-SkyMed constellation on 20140917 and 20140918. a) Comparison between observed, predicted and residual surface displacements. The black line outlines the outer caldera rim. The white lines mark the location of the inferred intra-caldera fault system (solid) and of the contracting body (dotted). As no slip is detected on the southern fault in the 24-hour period covered by the interferogram, the southern fault location is not constrained. Cauldrons, for which topography was not well constrained, are masked. b) Median of the posterior probability distribution of dip-slip on vertical fault segments, inferred from modelling. Color indicates the magnitude of slip. c) Standard deviation of the posterior probability distribution, using the same color scale as in b).

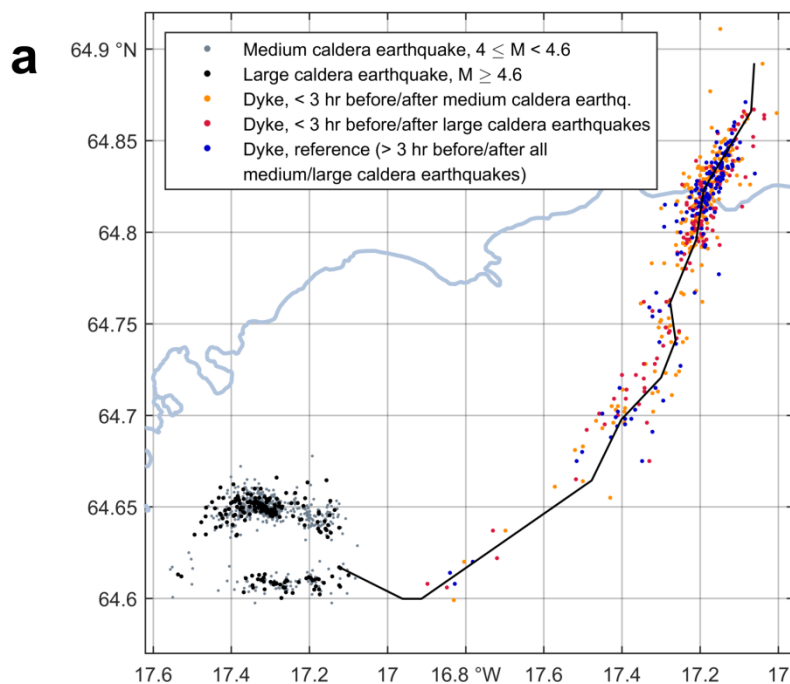
Fig. S8

Caldera-dike seismicity correlation. a) Geometry of correlated caldera-dike earthquakes. The dots show all dike earthquakes less than 2.5 km from the dike central line used for Figure 4a. b) Statistics of caldera-dyke earthquake correlations. Rate of dike earthquakes of magnitude $M \geq 0.8$ in time intervals shortly before and after large caldera earthquakes, of size ≥ 4.6 , compared with the rate in reference intervals, consisting of all times during the respective period which are at least 3 hours before and at least 3 hours after all $M \geq 4.0$ caldera earthquakes. c) An example of how data was chosen for the analysis (randomly chosen 3 days in October). Upper panel: caldera earthquakes $M > 4$. Lower panel: dike earthquakes during the same period. Blue bins mark three hours before and after caldera earthquakes with $M > 4.5$ used in the study. Yellow bins

1098 show data between significant ($M > 4$) caldera earthquakes, used to estimate background seismicity in the
1099 dike. Pink shaded bins show data that were not used in the analysis (due to possible overlapping effects).

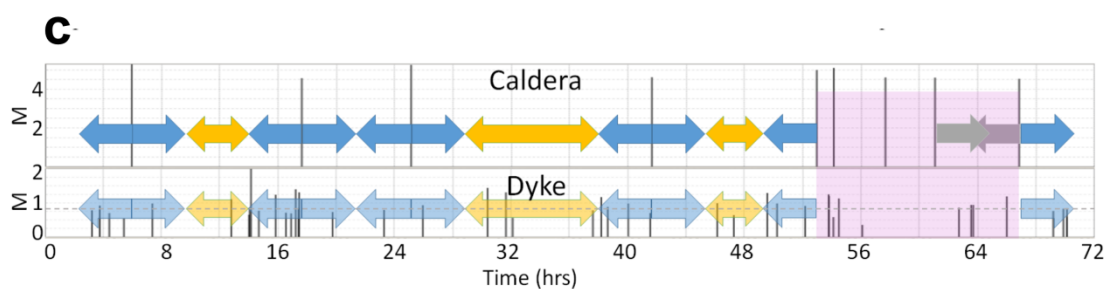
1100

1101



b

Period (2014)	Reference time, total days	Reference rate in dyke (earthq./hr.)	No. of $M \geq 4.6$ earthquakes in caldera	Intervals 0–3 hours before $M \geq 4.6$ caldera earthquakes			Intervals 0–3 hours after $M \geq 4.6$ caldera earthquakes		
				Total hours	No. of eq. in dyke	Rate (eq./hr.)	Total hours	No. of eq. in dyke	Rate (eq./hr.)
01–06 Sept.	3.1	7.04	8	19	132	6.85	19	140	7.26
07–12 Sept.	2.6	2.58	11	30	66	2.20	30	67	2.23
13–18 Sept.	3.1	1.39	9	21	30	1.40	21	27	1.26
19–24 Sept.	2.6	0.85	10	28	26	0.94	28	21	0.76
25–30 Sept.	1.3	0.47	10	29	23	0.81	29	20	0.70
Oct. 2014	5.0	0.14	74	179	44	0.25	179	47	0.26
Nov. 2014	4.2	0.14	25	64	19	0.30	64	12	0.19
Dec. 2014	11.0	0.09	15	42	5	0.12	42	3	0.07
Jan. 2015	14.8	0.19	13	39	10	0.26	39	9	0.23
1–21 Feb. 2015	18.6	0.10	3	9	1	0.11	9	3	0.33



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1104

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